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Goddard Space Flight Center

- - -

1973 GSFC BATTERY WORKSHOP

SECOND DAY

- - -

Greenbelt, Maryland

9:00 a. m.

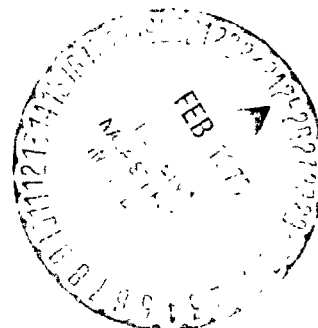
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P R O C E E D I N G S

FORD: Let us get started. Our first presentation will be given by Clint Jones. Clint?

JONES: Thank you, Floyd.

Maybe I had better have the first slide, please.

(Slide 117.)

It is by trapping the CO_2 into liquid nitrogen and freezing and then expanding it into a gas partitioner. Now here is a sketch, a rough outline of our apparatus. You could trap it with a liquid nitrogen trap.

Now, to kind of go briefly to what we do, the plates are cut out in a disk form, and it is ground into a fine powder where it is preweighed, and it is put into a flask where the acid is injected.

Next slide.

The acid is injected into the system through a syringe. It is injected through the stopper, where the sample is here, and also we have the sample flask sitting on the hotplate with a Stern apparatus built into it, with a Stern burner inside. Now, once the sample is dead and the acid is injected, CO_2 is evolved, and it is confined within this space from this gas flow bearer back. The CO_2 is evolved, confined within this space.

Now, on top of the flask we have a transducer to measure the pressure changes as the CO_2 evolves, and we have a helium inlet valve which we use for flushing out the sample prior to injecting the oxygen. So once the CO_2 has been evolved and confined in the area, we have a vacuum pulling on the complete system, back through here, and also back through the partition or the gas partitioner with the chromatograph.

And once this valve is open, the CO_2 is pulled out of this area back through here, down through a liquid nitrogen trap. Now this is in the Lewar containing liquid nitrogen. We have taken the sample collecting valve on the gas partitioner and made an extremely long coil -- I think it is about 12 feet long and we just kind of twirled it -- and it is submerged into liquid nitrogen.

As the gas passes, the CO_2 passes into liquid nitrogen. It is trapped here and is frozen. Over a period

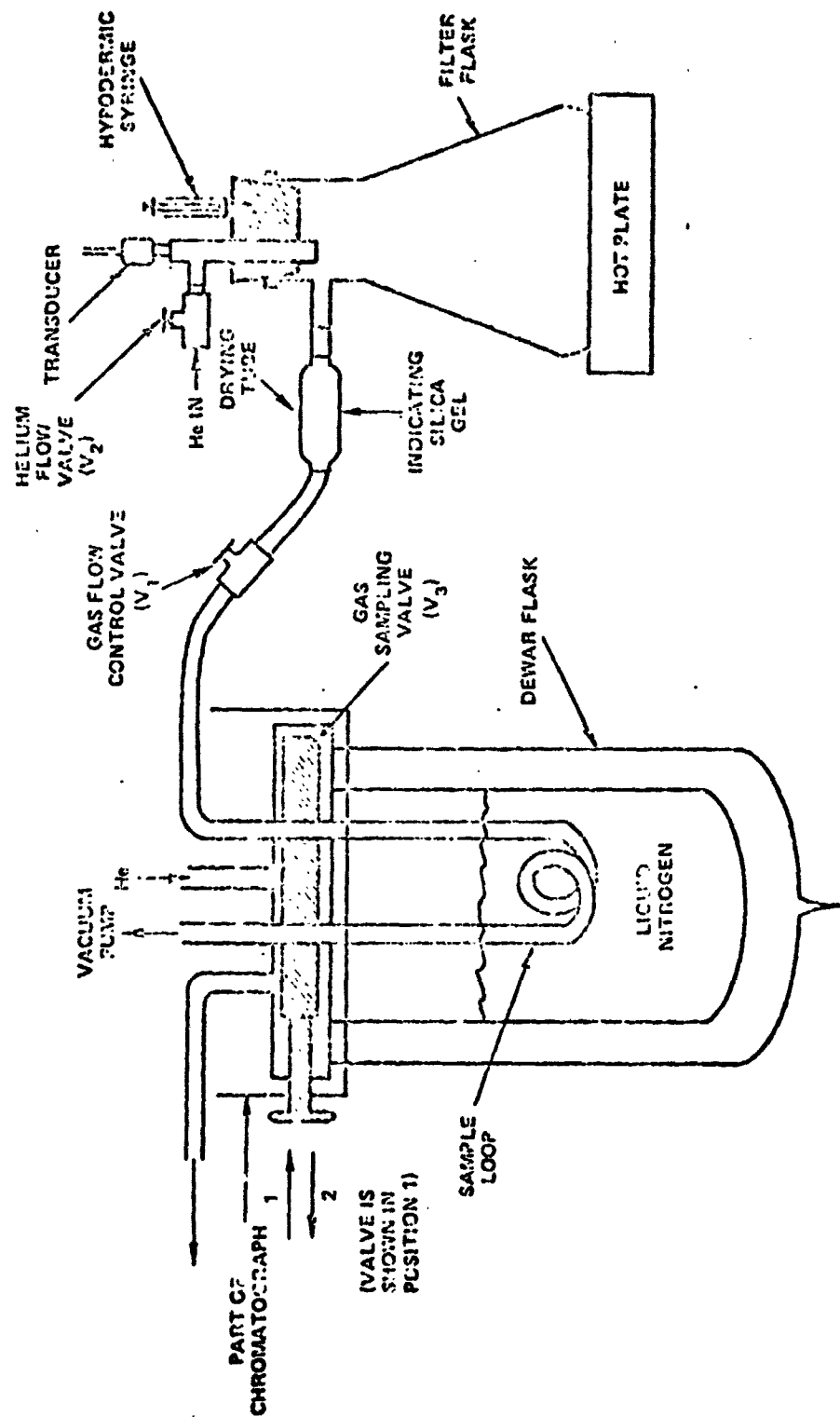


Figure 3. Apparatus for Determination of Carbonate in Plates

FIGURE 117

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of time we did this, and judging by the transducer which reads the pressure within here, we take it approximately back down to where it was prior to injecting the acid. And once we reach that corner of the transducer, the valve is closed. Okay.

The CO_2 is here in solid form. The vacuum is pulling through this entire system. It is closed up also. In other words is trapping, is confining the gas from this point to here. Well within, over this all, within this sample, this collecting tube.

So once that is accomplished the door is removed and replaced by a beaker filled with room temperature water, and allow approximately a couple minutes for the core to be brought back to room temperature. Okay.

Once the sample is brought back to room temperature, the gas is filtered back into gaseous form, the sample tube is open to the flow gas to the partitioner, which simply pushes the CO_2 in the gaseous form out of the sample collecting valve into the partitioner where it is read off as one solid unit of CO_2 on a recorder that we have also in the System.

And you get a nice distinguished peak without any composite, without oxygen or nitrogen showing up on it. It is a very neat way of detecting the carbonate, the amount of CO_2 . And after we have taken, or we have gotten a peak on the recorder, the sample of the peak height is taken back to a standard carrier which we use that has been calibrated using amounts of potassium carbonate.

And you just simply, by reading off the standard curves you have already established during the calibration of the partitioner, you go back, you try it against the peak height divisions on the paper versus grams of carbonate or potassium carbonate, and it is simply read out from that -- X amount of grams in a certain amount of weight.

And then, after you determine the amount in the sample, it is just scaled up from the sample to the plate to the cell. We have detected carbonate, and we have done analyses on several of the plates here, like the RAE, the AE, the OSO, and the SMS. And we found we have gotten pretty accurate results, or we think they are accurate.

After the sample, after we have taken it through the partitioner, the whole process, and we have read out on the standard curve exactly how much cadmium carbonate or nickel carbonate, depending on the plate, we have taken a sample

lh3

of the stuff that came out to X grams, and we have taken that amount and also ran it through the partitioner and compared the peaks to determine how accurate it was or how far off we were. And it came out pretty close, within a couple of divisions from regular procedure.

In looking at carbonate, we kind of set out to find out what were some of the problems. I guess we know the major problems of carbonate, what it does. We tried to find out what we could do about lowering the level of the carbonate and what is an acceptable level, which we haven't established yet.

But we did look at a washing process that we have used to lower the carbonate level. When I am talking about carbonate it is mostly cadmium carbonate or nickel carbonate. Potassium carbonate contributes very small to the total carbonate that we found in the plates, a very small amount.

The main problem is the cadmium or the nickel carbonate in that form in the plates. And one method that we are using to lower this level is a washing technique using sodium hydroxide, 20 percent sodium hydroxide. And what we do is take the plate after it's weighed, and we submerge it in that at approximately 50°C, and it stays there for about three hours at that temperature.

The tray is removed, put into hot deionized water, or washed in hot deionized water till it is caustic free when you wash all the sodium hydroxide off of it. And after that's completely dried, we ran another sample of the plate and we found that the cadmium carbonate -- in this particular case it was a negative plate -- was substantially lower, I guess anywhere around 40 percent lower than it was prior to that. And that is one way that we found we could eliminate the cadmium or the nickel carbonate in a plate, which is we think the main problem as far as carbonate contamination is concerned.

Now, we ran a couple other small experiments trying to find out exactly what or where was the carbonate mainly coming into, manufactured into the plates, where it was coming about or what was the mechanism now.

The mechanism for forming cadmium carbonate after the cell has been sealed -- I don't think anyone really knows what goes on in there after that, but we found that we think that one of the sources might be the breakdown of the separator or the electrolyte. And under the conditions of cycling, we found that carbonate level increases as cycles like ours

1h4

increase. We found also that the cadmium and nickel carbonate in some plates that we looked at were -- the cadmium carbonate tends to increase from the bottom up on 20 amp. hour cells. This is mostly what we have done. We are working with 20 amp. hours.

And we also looked at some of the effects of leaving the cells out in the open. Some we dried in the vacuum oven, and some we dried in the inert atmosphere or nitrous atmosphere.

And we found that the only increase in carbonate that came out of leaving it out in the atmosphere or leaving it open was the potassium carbonate. And it increased substantially. Well, not substantially, but it was an increase. If cells were just, say, washed and left open to the atmosphere.

In a vacuum oven, we found that that was about as bad in some cases. In a couple of cases, it came out even more, so it was kind of unusual. But the ones we put in the vacuum oven came out a little bit more potassium carbonate-wise than the ones that were just left out in the atmosphere. I don't have an explanation for that.

And the ones that were in the nitrous atmosphere were essentially lower than both of the other two. So there is the absorbing CO_2 from the air in forming potassium carbonate. Now what happens after the potassium carbonate is there? Does it contribute to forming nickel carbonate or cadmium carbonate? We haven't really established that now.

I don't know if anyone here has done any work in carbonate analysis or in the potassium carbonate, but if so, I would like very much to discuss it with them because there are a lot of answers we don't have. We are just looking at them, so I will appreciate any information from anybody, or a discussion of it, who has done some work in carbonate analysis or looking at particularly cadmium and nickel carbonate in the plates.

Thank you.

FORD: Thank you.

Are there any questions?

DUNLOP: When you take a nickel-cadmium cell that is new from the manufacturer and you strike the electrolyte, you normally find 9 or 10 percent potassium carbonate in the electrolyte. You know the manufacturer isn't putting it in

1h5

in that form in the electrolyte. You do an analysis on his sample, and it is almost a trace element of carbonate. You assume then that this carbonate comes from the plates?

JONES: In the cells, it is built into the cells during that, so I would assume the electrolyte attracts it out of the plates, yes.

DUNLOP: The question you really run into here is if you take your plates and run them through a formation process, and you eliminate the carbonate from the plates in the formation process, when then do you pick it up between the formation process and the final assembly if it is not picked up in the air.

You seem to indicate the carbonate wasn't picked up in the air.

JONES: Well, now, to pinpoint a specific area exactly where the potassium carbonate or the nickel carbonate is picked up in the cell, it would be kind of hard to pinpoint it. It could be any time that it is exposed to the air, during washing or even during impregnation or something.

I don't know exactly what area that I would pinpoint it, this is where it is coming in at, or this is where most of it is picked up. I couldn't say that.

SEIGER: Could you describe, after you took the plates and washed them with sodium hydroxide and washed them with water, could you describe the process of drying? And also I would like to hear how much the content was reduced.

JONES: Okay. For drying I use a nitrous atmosphere. I took them and put them in a controlled atmosphere chamber after washing. Depending on the plate, it was around anywhere from 35 to 40 percent, according to figures we got. Also, if you washed it a second time, it also brought it down a little farther.

SEIGER: What kind of levels are these in grams per plate?

JONES: Let me see, the plates that we ran --

SEIGER: Were there nickel species present in the carbonate?

JONES: I was working with the negative, so it would

1h6

be potassium carbonate.

SEIGER: Fine. What percent of potassium species was present as potassium carbonate?

JONES: I think, of the active material in the negative plate, it was around 12 percent, in the negative plates. Now the positive plates were a little less than that.

KROGER: I have two practical questions. What are your time requirements per sample? In other words, how many samples can you run per hour in this procedure.

JONES: Okay, the whole procedure takes about a half an hour, 25 minutes.

KROGER: The second one is what is your sensitivity?

JONES: You can detect about one milligram of carbonate.

KROGER: What is that -- potassium carbonate?

JONES: Cadmium or nickel carbonate.

KROGER: What are the samples?

JONES: Approximate weight of 1.2 grams.

KROGER: Okay.

FORD: Okay. Other questions?

MR. LURIE: After you have the hot ionized water wash, how do you determine plate polarities?

JONES: We use a phenolphthalein check in the wash.

MR. LURIE: So you didn't actually check the plates for hydroxide ion concentration?

JONES: Just the wash.

HALPERT: I want to say this procedure is described in a report doing analysis of the plates storing carbonates, nitrates, hydroxides, positives, negatives, separators and complete procedures. It will be out shortly. We have the final copies at this point.

One of the things I would like to stress that

1h7 Clinton found was not so much the potassium carbonate being a problem, because you can control that, at least by working with it in proper washing and putting it in inert atmosphere, you can control that.

The plates did seem to contain a large amount of cadmium carbonate or nickel carbonate which was not washed, or washed out with hot water, in which potassium carbonate was determined. After washing with the water, after taking a sample of hot water into which the plate had been dipped and the potassium carbonate removed, then these plates were put into this apparatus Clint has described and carbonate was determined.

So what he is talking about now, in essence, is large amounts of carbonates in the plates: nickel carbonate in the positive, cadmium carbonate in the negative and not so much potassium carbonate. Potassium carbonate is washed out with ordinary water, warm water.

BOGNER: Do we know what levels of carbonate are really harmful, or what the effect of carbonate really does?

JONES: No. We haven't determined that. When it really gets to be detrimental, or what is a safe level, or what would happen if it was all gone.

FORD: I don't know of any real control test that has ever been run to demonstrate the effect of carbonate.

BOGNER: There was a paper given a couple of years ago by somebody from GE, I guess, over in Europe. I think it will probably tell more about it. Fifty percent levels of carbonate are there before you can see anything, is that right? One of your people, I think the plant manager, Cototi, gave a paper.

RAMPEL: Up to 50 percent -- was it a little over 30 percent?

STEPHENSON: I am Stephenson from Motorola. You are saying you see primarily nickel carbonate and cadmium carbonate in the display. I don't see by your apparatus that you can distinguish between potassium carbonate and nickel carbonate. You are actually measuring total carbon dioxide liberated from the plate. Are you using an auxiliary method?

JONES: Prior to subjecting it to this method, the potassium carbonate is washed out.

STEPHENSON: You are assuming it is washed out. You don't know if it is washed out for certain.

JONES: We don't know if it is all washed out, no. We are assuming.

1h8

MIKKELSON: Could you analyze these plates at the time of absorption with an atomic emission spectrometer to determine the potassium content before analysis, to determine for sure if indeed you are looking at potassium carbonate?

JONES: We haven't. It could be done, yes.

MIKKELSON: What I am saying is you could have potassium carbonate in a plate that you are not washing out in the first wash sequence, but you are seeing it when you add strong acid to the plate material. It is a subtle distinction, but it is the whole argument of your paper: where is the carbonate coming from, is it indeed potassium carbonate?

FORD: Yes. I would like to comment. There was some work done along those lines in the last year at the ending of the contract with EP on process variables, where they were looking at the carbonate problem, where it comes from, and a process as to how to analyze it.

They did find out that the amount of carbonate they would measure off of plates, there was more carbonate there than could be accounted for by the potassium ions they found in the plates. Okay. Now, I don't know what the numbers were.

LURIE: There is definitely a partitioning of all these species when you take a plate and you clean it by soaking it, by having it bleached, and ions like sodium and potassium tended to stick rather tenaciously on the nickel surface. And you don't get all of them out, nor do you remove all of the hydroxyl ions when the hot water has turned neutral.

In other words, if you wash and you monitor the hydroxyl ion concentration of the wash water, you will reach a neutral wash water before the plate has lost all of its hydroxide within the sensitivity of a normal range.

JONES: What you are saying is that there is possibly still the cadmium carbonate still there.

LURIE: There is probably still potassium hydroxide present in your plate after your wash even though your wash water shows neutral. And it probably is necessary to do an elementary analysis of the plate, rather than the wash water, because it is in fact the plate you are interested in.

There is a partitioning, and the partitioning is not way over on one side.

JONES: You are saying we could possibly overlook a

1h9

significant amount of potassium ions?

LURIE: Yes.

FORD: Okay. The gentleman in the back?

LACKNER: Joe Lackner. I am afraid I will have to make my annual statement about carbonate. The Defense Research Board did extensive work on carbonates in the late and mid 1950's. This was reported in the Electrochemical Journal, including the analysis and the tolerance levels. We have done extensive work in the 60's particularly with aircraft batteries, taking it out.

The level we specified for satellites is less than 4 percent by weight density. The manufacturing process is such that it will give you a 10, 12 percent. CO_2 is very tenacious with potassium hydroxide so you can't help but get it into the plate structure during manufacture.

The sinter plate is porous to about 80 percent, so just washing it isn't going to get your carbonate out. You have to work it out. You have to charge and discharge and work it up. So just washing it won't get you anywhere.

We usually specify that the carbonate level has to be less than 4 percent after a minimum of three charge-discharge cycles, particularly including a high temperature cycle. High temperature will drive it out, but you have to work it up by charge and discharge by using a flushing technique.

When you go through the effects of carbonate, you can get very misleading results, because if you have an open pore structure you can get away with as high as maybe 8 percent or 10 percent carbonate, and it doesn't block the pores.

If you have a very tight pore structure, and it is more pronounced, the carbonate has a masking effect. It affects your low temperature operation. It affects your high rate of discharge. It can give you a sleep effect. We have several papers on this but it is in the open literature. I sort of hesitate to come up every year and mention this, because I think it's old hat.

FORD: Thank you.

STEINHAUER: I wonder if you couldn't correct your results as to whether there is still potassium carbonate or cadmium carbonate by analyzing your acid solution in your apparatus?

JONES: We could check it. There is a possibility we could look into that.

FORD: Let's take one more question.

1h10

LACKNER: With regard to levels of carbonate that might be harmful, this is a part question. Isn't it fair to assume that the nickel and cadmium carbonates are not electrochemically active, and therefore that is lost material that could account for the so-called coefficient of utilization, so-called inefficiencies, impregnation? Any comments on that?

FORD: Anyone want to field that question? Apparently not. Okay. Thank you, Clint.

I would like to move on. At this time, we have Dr. Font from the SAFT Corporation of France who would like to give a presentation entitled, "Memory Effect on Nickel-Cadmium Cells." Dr. Font.

FONT: Thank you.

Nickel-cadmium memory effect is a manifestation of the memory effect on nickel-cadmium cells, is a presence of a second plateau that joins the discharge of the cells at 1 point millivolts lower voltage level, approximately 105 volts per cell, for one cell.

The second plateau is observed essentially on discharge after charge for three different conditions. The first one is on continuous floating, mainly telephone applications. You can observe after several months of floating a second plateau on the third discharge.

A second possibility is to observe the second plateau on charge retention at very high temperatures, especially higher than 45° C. The second point is one point of interest for us, is to observe the second plateau in a continuous cycling, especially for low orbit applications.

The second plateau generally is eliminated, but only temporarily after one or some complete discharge of the cell down to one volt and appears to be related to a well defined process. We have therefore measurements on electrode potentials versus oxide mercury on the record during the discharge of the cell, and we have seen that the negative was responsible for the second plateau.

(Slide 118)

This is a schematic figure in which you can see the measurement we have made. You see the second plateau on the negative electrode at about one millivolt less than the normal value. This takes into account the second plateau on the cells. The first analysis of the causes of the phenomena has been contacted, and we have looked at several points. One is roll-off electrolyte and carbonate influence; second, the influence of

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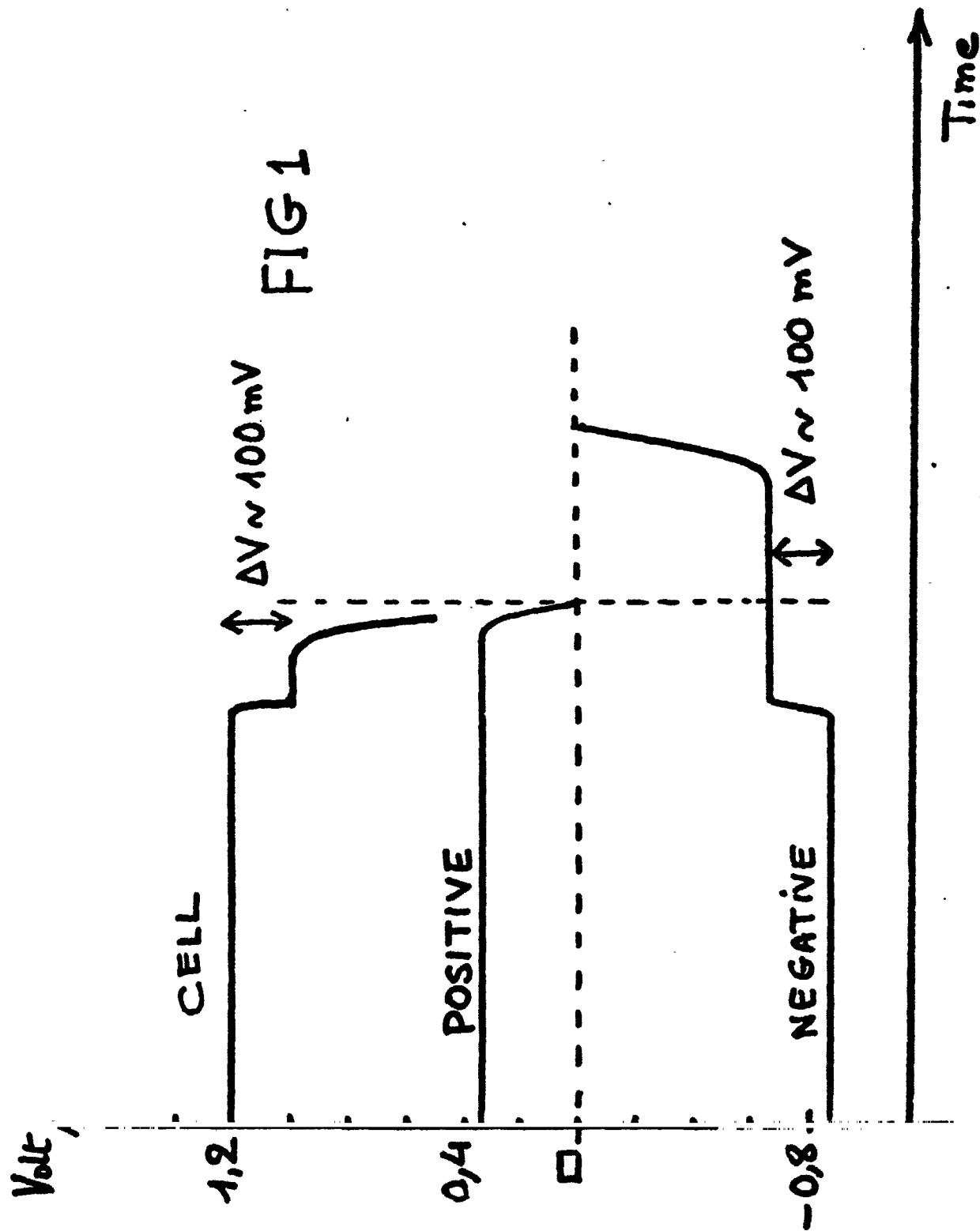


FIGURE 118

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products like peroxide H_2O_2 minus produced during overcharge, and the consideration of the negative electrode.

This analysis has shown that point one and mainly point two, that means the electrolyte or products like hydroxide, could account for the second plateau but with a short duration, generally less than 10 percent of the total available capacity on the cell.

Three is the concentration of the negative electrode. It seems to be the essential factor and particularly the nickel hydroxide content on the negative electrode. Why do we have a high voltage content on the negative electrode? There are two possibilities.

One is the corrosion of the sinter of nickel support of the plate by the acid solution of impregnation during the clinical process. The second is that in the solution of impregnation, even for the negative impregnation, we have always a small amount of nickel which can co-precipitate with the cadmium hydroxide during the process.

So this nickel content on the negative plate, after a chemical impregnation, can vary around a value which represents about 5 percent of the capacity of the negative electrode.

(Slide 119.)

On Figure 2, it will represent the role of the nickel hydroxide content on the negative plate, and we have tried to demonstrate the effect on the charge retention at $50^\circ C$. The initial capacity, which here is C zero after charge and discharge cycles, some charge and discharge cycles.

We have performed the charge retention at $50^\circ C$ for 11 days. On the continuous curve you see that the capacity charge retention decreases with increasing any $2+$ content on the negative electrode. These are the points A, B, and C on the continuous curve.

On the dotted line curve, you see the capacity discharge at the second plateau increases with increasing the nickel $2+$ content. These are the black points. For the point C we consider the capacity at the second plateau is minimized, because we have a low value of capacity on charge retention tests. It corresponds to the point at 0.3 nickel $2+$ content.

Well, we have verified also the role of nickel $2+$ content on the continuous partial cycling at a temperature of $20^\circ C$, with a depth of discharge of 30 percent in the low orbit condition cycling. We have two series of cells, one in which the negative plates have been impregnated by the standoff process without any special care.

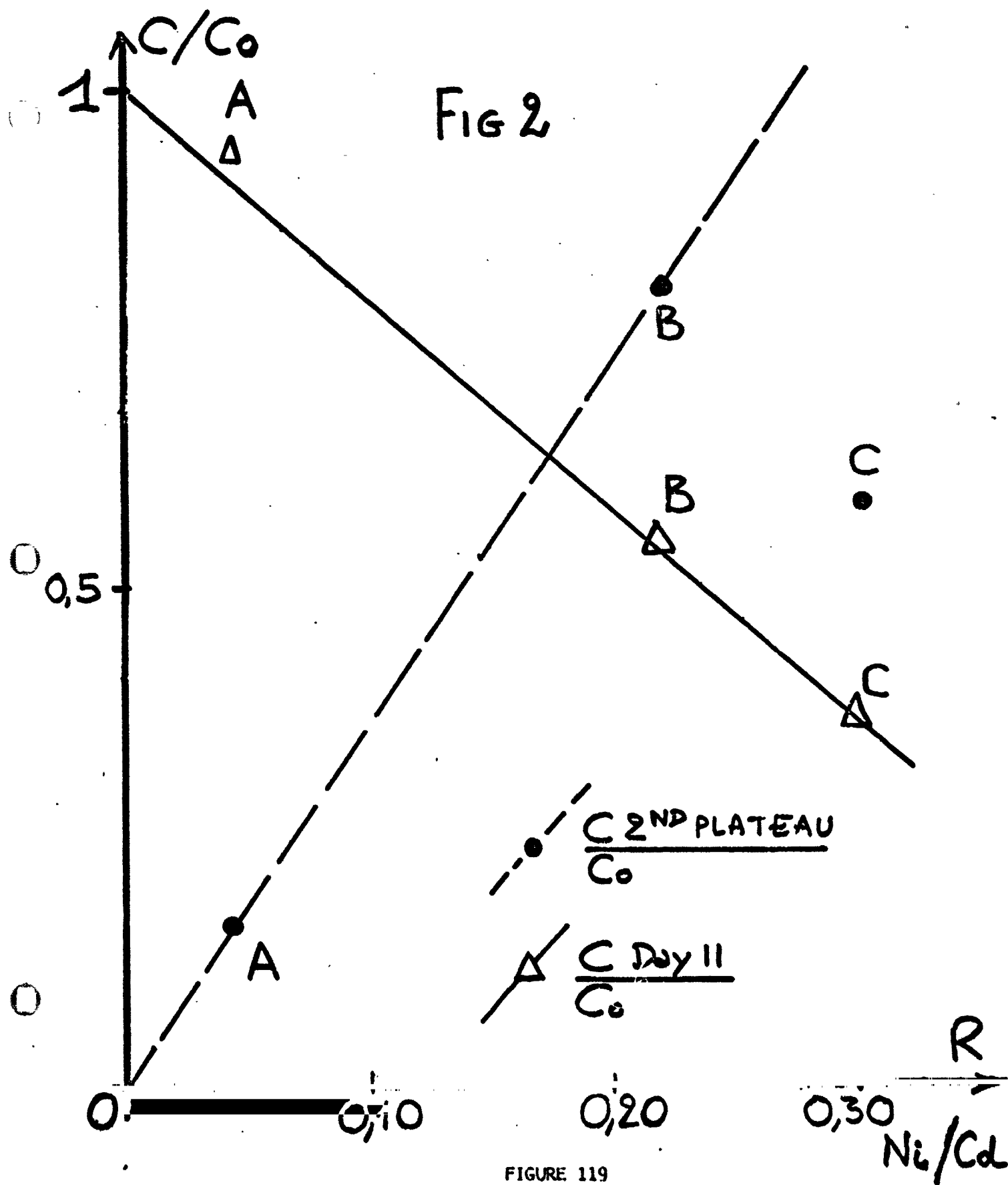


FIGURE 119

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A second series of plates in which impregnation is made by your special processing in order to minimize or to decrease at the maximum the nickel content on the negative plate.

If we can look at Figure 3.

(Slide 120.)

You see here on Figure 3 the discharge curve of these two theories. After seven about cycles on the standard impregnation, you observe a pronounced second plateau, and there is no second plateau for the same capacity with a special impregnation. After about 4,000 cycles the second plateau is more pronounced for the standard impregnation, and we begin to have a little second plateau with the special impregnation but associated with a loss of capacity.

So what is important to remember is that if we decrease the second plateau level we can have a loss of capacity on negative electrode because these cells were cells in which the negative and positive electrode have a very close capacity. So the loss we observe is due really to the negative electrode.

Well, I want to have some preliminary conclusion, because this is a very preliminary work on this problem. All we can say up to now is that the negative electrode is responsible for what is called the memory effect on the nickel-cadmium cells.

The nickel content on the negative electrodes seems to be related to the presence of a second plateau during discharge of the cell, also the role of nickel is clearly obvious, the mechanism is not yet clarified. Does the nickel $2+$ act as a catalyst or an expander or is there any formation of the complex nickel-cadmium? Up to now we have not been able to determine exactly what was this mechanism.

The absence of nickel $2+$ of the negative electrode seems to have a detrimental effect with time on the capacity available at this electrode. Our results are in agreement with a paper presented by Pozin Gamaskin, and published by the Journal of Applied Chemistry of USSR, if you want it.

And in this paper it states the second plateau can be attributed to the formation of intermetallic compounds which they have determined to be $NE_5 CD_{21}$. That is all about the memory effect.

GINER: Jose Giner. I have read the Russian paper, and I see you agree very much with this type of work.

FONT: Yes.

GINER: I would like to put out a word of caution that

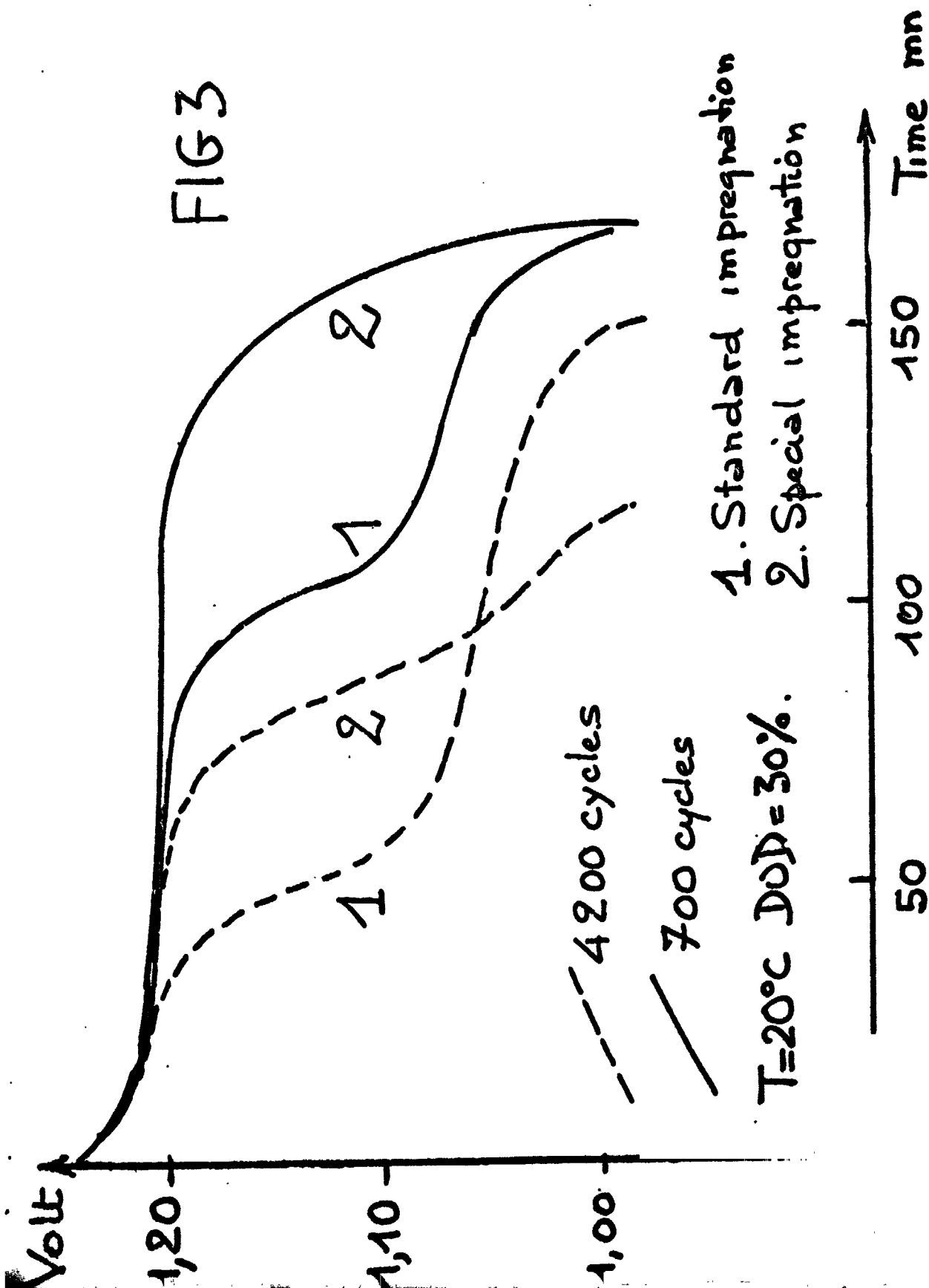


FIGURE 120

1h13

the nickel electrode does something too when you work with nickel hydrogen cells. It is something very similar to a memory effect. It happens in partial cycling. It's the nickel electrode. The effect is due to the nickel electrode.

Still more interesting, you can erase this memory effect by total discharging.

FONT: At what voltage do you observe this memory effect?

GINER: Similar to loss of discharge trailing. It's not very well defined, but you can see this memory effect. It is nickel.

FONT: Yes, we have observed. For example, we are moving some electrolyte or by addition of peroxides that we can have a second plateau due to this kind of thing. It is not a very long or a very large amount. It is always less than 10 percent. It is difficult to explain the second plateau of 50 percent of capacity only by electrolyte effect or peroxide effect, and I would like to know exactly what is the voltage you observed on the second plateau, because it's at the positive electrode you have a second plateau at 0.8 volts which is different.

GINER: Yes. In addition to the second plateau, you get a third plateau, about .8. We think it's very sensitive.

FONT: Yes, it is a well known effect at 0.8 volts.

GINER: Yes, you lose that easily.

FONT: What is the amount of the second plateau at about 1 volt that you observed?

GINER: I am not ready to discuss the exact amount, but it's very similar to what one reaches about the memory effect.

FONT: Okay.

DUNLOP: There will be some data of this type presented this afternoon. Frankly, you do see a loss of voltage with the nickel-hydrogen with cycling, which is somewhat like you see with the nickel-cadmium but not as pronounced.

FONT: It's less.

DUNLOP: I would agree with what you said. There is some effect with the nickel cycling in terms of loss of voltage, but it doesn't seem quite as pronounced as this excessive memory effect that you sometimes observe with nickel-cadmium.

1h14

FONT: We have seen also this kind of figure, but it was mainly with the plateau at 0.8 volts. It was not so pronounced as nickel cadmium.

KROGER: In the past few years we have done some work at this point, the same work as the U. S. Air Force contract work as reported in the final report about memories. It was on the side-line, and I also gave two papers in electrochemical analysis.

In our opinion the memory has several, has two reasons. For the first we found the positive electrode you have a lack of charge effect that kills the capacity, but only temporarily. You can restore it.

The second thing is you have something which is much more profound in the negative electrode. The step you observed, 100, 150 millivolts, depending upon the discharge rate, that is definitely caused by the negative and almost impossible to get rid of it in a sealed cell.

FONT: Excuse me. If you don't?

KROGER: If you have a truly sealed cell, you cannot get rid of the step in the negative. If you have a possibility to vent and you can put back the original precharge, whatever you call it, then we can get rid of it.

The third observation I would like to make is in our opinion the memory effect very clearly is associated with the geometry of the cell. You have a thick pane to go through to get memory in round cells. In plain cells it is easier, depending on the configuration of the plates. You can produce all types of severity of the memory.

FONT: It doesn't take me so much on the last thing. I think that in the memory aspect there are two points in the memory effect. My concern was the negative electrode I am not speaking always about the loss of potential in the opposite curve which also can be something with a positive efficiency.

But with respect to the negative electrode, sometimes you can't observe the second plateau at one millivolt or less, because you have a cell where you have a large recharge, and you have a second plateau, but it is on the precharge, and you don't see it, but it exists and along the cycle it begins to appear.

So according to your precharge level, you can have cells in which you don't see a second plateau because you have a high precharge. I don't know if we have to associate it with the geometry. I would prefer that it was associated with the design of the cell. Perhaps in some cells you have a different

1h15

negative to positive ratio design or a different charge adjustment which gives you different ideas at the second plateau.

STEINHAEUER: Does your work or the Russian paper, if this effect is true of the plus-two nickel, go into concentration effects with regard to time dependency with how soon you would observe this or how severe it would get?

FONT: It doesn't present results in time dependency. It's only a presentation on the effect of the nickel 2+, but it doesn't speak about the different kinds of regimes or duration.

STEINHAEUER: With regard to the amount of nickel that might be present?

FONT: Yes.

FORD: Other questions, comments?

PALANDATI: I was wondering if you have any feelers to whether the discharge rates may have an important effect on the so-called memory effect -- in other words, if you were to run a higher discharge rate?

FONT: Well, for French national agency we have had lifetime evaluation on cylindrical cells years ago, and I have looked at the results of the second plateaus of cells in different depths of discharge and different temperature. And there are some general rules and I don't know if they are associated with depth of discharge, temperature, or the rate of discharge.

But there are some general rules in which you observe, for example, very low depths of discharge, very high, severe second plateau at high temperatures. For example, at low temperatures you observe perfectly a second plateau when you are at high depths of discharge. It rises at low depths of discharge.

There are some general rules. I have not looked into all the details of that.

PALANDATI: The reason I bring this up, I work mainly with silver-zinc and I find I also see something similar to this in silver-zinc. I would have to attribute it to the fact that on a silver-zinc cell you lose your zinc material, your negative material. It slumps off the plate. Eventually you get to the point where you have more positive than you have zinc.

At this point, I find that we would, with the satellite application with real low rates, that I definitely do see a second plateau take place roughly after about 75 percent of the depth of discharge, 75 percent of capacity has been removed. Similar tests have been used at higher rates than we do that might possibly be discharge rates that have an effect.

1h16

FONT: Yes, perhaps.

FORD: All right, one more, then we will move on.

GASTON: I have a comment on silver-zinc. Ordinarily you have your discharge because you have two species.

PALANDATI: I am talking about the normal level.

GASTON: You mentioned two plateaus.

PALANDATI: Definitely you see your peroxide.

GASTON: All right. I would like to go back and address myself to the paper. On Slide 120, I wonder if we can go back to Slide 120 again and just show it for one second.

The question I have on it is the following. I was left with the understanding that possibly the special impregnation reduces the effect of the second plateau, or maybe it retards it. How many samples were actually tested, or could it be an individual difference, sample to sample?

FONT: Up to now the standard deviation is very significant for the explanation of the phenomena.

Thank you very much.

FORD: Thank you, Dr. Font.

At this time Jerry Halpert will be the session chairman for the duration of the morning session. Jerry?

HALPERT: This session will deal mainly with testing modeling prediction. Since we have a number of speakers and some very interesting papers, I would like to move right on and start with Jim Harkness of NAD/Crane, who is going to talk briefly about his new automatic acquisition equipment, at NAD/Crane.

HARKNESS: A year ago last September, NAD/Crane put into operation a new automatic data acquisition and control system known as ADAC. This system was funded by NASA/Goddard at a basic cost of \$340,000. Since that time, we have added \$200,000 to the system.

Could I have the first slide, please?

(Slide 121.)

This system was manufactured and put together both hardware and software programming by a company in Anaheim,

1h17

California whose name is Data Incorporated. Can we get the lights down a little bit on these? Okay, that's fine. As you can see, we do have a pretty shade of blue on it and shown is the system and that's the doors that are on the system because there is not a whole lot to see as far as printed circuit boards inside.

Also shown are a couple of the teletypes, which are the peripheral equipment, and right over to the right also, right over here which you can't see very well, is the CRT, and of course these items are used for both inputting our communicating to the system and also for reports that come out of the system.

Next slide, please.

(Slide 122.)

This is another view. As you can see here, the CRT and this is the line printer, and actually the line printer is about ten times faster than the teletypes we have.

Next slide.

(Slide 123.)

This is the NASA sticker right up top here. This is the heart of the system. It is a Honeywell 316 general purpose minicomputer. It has -- we do have 32K core memory with the system. Most of the work ng programs of the system are done, are located in this core memory. As you see, we also have two magnetic tape units which the data is recorded on.

May I have the next slide, please?

(Slide 124.)

This is a picture of the system with naturally the doors off. Available with this system is 3,000 data channels. We read at an accuracy of one millivolt, and that was designed into the system using 50-foot data leads. This can't be seen very well here, but there is a thousand data points in this cabinet, and the next two cabinets to come over to your left also contain a thousand data points.

They are on printed circuit boards, use the concept of read relays, and there are ten channels per board, so you have a hundred boards per rack, and these other two racks are the same as this one. As you can see up to the top are the digitizers which we use flukes 8300A model. They read 40 channels per second. And the normal scan that we can go through of the entire 3,000 channels is 2.4 minutes. That is the



FIGURE 121



FIGURE 122



FIGURE 123



FIGURE 124

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1h18

normal scan. Now, this system is expandable to 5,000 channel points, and we still keep our time base of 2.4 minutes; in other words, we go through every data channel that we have in 2.4 minutes, and we can also cut it down and read them every 36 seconds. Not the full 3,000 points, but, say, an individual pack may be read four times within that 2.4 minute scan, if we needed to do this as far as a special test where we did not want to reverse the cells or anything like this. We would read them sooner. But normal cycling would be 2.4 minute scan.

Every time we scan a pack we read the data, and it is put on magnetic tape units. We have two of them here. When one gets full, it automatically switches down, prints out a report, and it goes to the next tape deck. That way we do not lose the data.

If both tape decks would go bad, would not work, the system would not shut down because we feel it would be more detrimental to shut the system down and leave the pack on open circuit where they would be in charge and discharge, than it would be to -- we wouldn't mind losing a little bit of data.

The digitizers, if both of them would go out the system automatically goes down because we wouldn't know what we were reading. we wouldn't know how to control, so we would want a shutdown on that, and it does. Therefore one is only on a line and one is a backup. If the one kicks off, it goes to the next one; if it kicks off, the system goes down.

We also control with this system, which we call the data R cards which are digital to resistance cards. Each card programs a programmable pilot supply, and it puts out resistance out there as far as where you want, you know, how much resistance you want for current and how much for voltage.

It also has contacts on there as far as four relays which program our control units which contain the heavy duty relays for the charge-discharge current. That's so you couldn't put those currents through these cards.

We set up limits on our programs to where we check currents on the packs and we check voltages to where if we have marginal and emergency limits, to where if a pack was, say, on discharge we want to know if a cell gets down to, say, one volt. Well, marginal limit would come out.

If we also say it would just tell us about it, the alarm is sounded and the thing is printed out on a teletype identifying what, and so forth. If the emergency limit would happen, say the cell got to .5 volts -- and we consider that failure on a lot of the packs, then it would print it out and the alarm would be sounded and it would shut the pack off. It

1h19 would go in open circuit.

Next slide, please.

(Slide 125.)

Okay. These are the controlling units I was talking about where each pack does have its individual power supply, and this is located right behind the main system.

Next slide.

(Slide 126.)

All the data channels come out when we go through the one building into another building. This is our control panel we call. where each one of these cables that come in is data tails. So all 3,000 channels are out here wired, and as we wire up the pack we just plug them in to the main board. It is located centrally out here where our chambers are.

And the heavy leads are the charge-discharge leads coming from the power supply, which is another board located behind this one.

Next slide, please.

(Slide 127.)

And finally, we come down to the battery types that are in the chamber.

Could I have the viewgraph now, please?

(Slide 128.)

As you know, we do many flight projects out here, and these are some of our objectives, to evaluate them and to assist the technical officers here at Goddard Space Flight Center.

Next slide, please, or viewgraph.

(Slide 129.)

These are some of the flight projects that are now running. AE has just finished its acceptance to us and should be starting its flight cycling next week. which is just kind of right before the satellites go up. I understand they go in December.

I believe that's it. You wanted it short.



FIGURE 126



FIGURE 125



FIGURE 127

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SATELLITE FLIGHT PROJECTS FY '73

SAS

OSO

ATS

IMP

OAQ

PE

ERTS

AE

RAE

SMS

ADDED FY 74

IME

ITOS

IUE

FIGURE 129

OBJECTIVE OF THE SATELLITE FLIGHT PROJECTS

1. Test and evaluate flight cells
2. Perform pre-and post-flight simulation
3. Supply supporting data to project offices

FIGURE 128

1h20

HALPERT: Any questions for Jim?

WERTHEIM: Max Wertheim, Grumman. I see you have voltage protection at two levels. Do you have overvoltage protection?

HARKNESS: Yes. We can set upper limits or lower limits.

WERTHEIM: The same thing where you have an alarm?

HARKNESS: Okay. We want to run a battery pack with a voltage number 145. I can set a marginal limit where, if normally I consult a technical officer, I say okay, what happens, when do you want to know when an unbalance occurs. And they say if a cell gets up to 147 we would like to know about it. So we put the limit in. Any time that cell gets up to 147 we get a marginal alarm on it.

And we can set the emergency at 150, or we can set it at the same point. It all depends.

WERTHEIM: How about pressure?

HARKNESS: Oh, I forgot that. Thank you. Naturally if there are gauges on cells the pressures are read manually. That is one manual operation we didn't get away from. We tried to put in pressure transducers on all the cells, therefore pressures are read in volts. We do have, we put in curves of that pressure transducer into the system. Then your pressure readings come out in engineering units in p.s.i.a. within accuracy of .1 p.s.i.a.

Now, this also brings a point as far as temperature. We use thermisters, therefore our readings then are voltage and it takes up the curve. and it reads them out in engineering units of degrees C, accuracy of .1 degrees C.

WERTHEIM: How about overpressure protection?

HARKNESS: The same thing, and temperature the same thing. We also have a program in there we do have essentially six temperature chambers, and you know if a temperature chamber goes bad you've got some problems. So we do have a program that is read every half hour that reads the ambient temperatures of the chambers, and if one gets out we have the same type of thing. Of course it's only a marginal alarm. It can't be an emergency. It can't shut the chamber down, but it tells the operator, he goes out there and finds out what's going on.

WERTHEIM: All right. One other question I have. Do you have automatic orbital timing control, that is, can you

1h21

set a charge and a discharge and have cells go through an automatic cycle as well?

HARKNESS: Well, I am assuming -- maybe I don't follow the question right, but the cells automatically charge and discharge with the system.

WERTHEIM: You are saying yes to my question.

HARKNESS: Yes. Maybe I didn't make that clear. The thing is that we don't have any set time. In other words, we can start all, say all 90-minute packs do not have to start at the same time. Okay. Each pack has its own time base and cycle.

Don, did you want to make a comment on this?

MAINS: I might clarify that a little bit. The computer is not only the central processor but also the central controller. We can input a test plan of up to 128 steps in any time limit, any sequence of charge-discharge and open circuit. That can be run repeatedly for days or years or minutes. So we pretty much have a complete open programming capability in that sense.

HARKNESS: I would like to make one comment, since we are going pretty fast. I told you we had 32 K of core memory. We also have an additional 131 K mass memory storage. This is a drum which I guess maybe you would have thought about later, because naturally we have to have some place where we put these pack programs on.

Also, as of this week we are receiving another drum and two magnetic tape units on which we will be doing our own data processing as far as cutting down, because, as you can see, if we are reading all these data points every 2.4 minutes and all this data is recorded, that we have quite a data reduction thing to go through.

HENDEE: Ed Hendee, Telesat. I assume you use these for simulations.

HARKNESS: Yes.

HENDEE: I am wondering what the thermal control system is like, how you control your thermal requirements.

HARKNESS: Environmental changes. Is this what you mean?

HENDEE: I am talking about the logic. In other words, how do you drive -- what is your logic, are you just driving the batteries by driving the mounting surface to have a feed-

1h22

back to test?

HARKNESS: You are asking what is our pack configuration?

HENDEE: No. I am wondering how you literally drive, what is your control concept for driving the batteries temperature-wise?

HARKNESS: Temperature-wise? Don, do you want to comment on this?

MAINS: We do not try to control the temperature changes with the system. At the time we were developing the system, the best control we could get was worse than what the chambers could control the temperatures themselves. So we did not incorporate a close the loop operation on the environmental changes itself.

They are set up, we hand program the chamber with the standard disk type controller, or we normally operate at a fixed temperature. We do not do a closed loop operation on chambers. The electrical testing of the batteries is closed loop with the system. Environmental temperatures are not.

HENDEE: You just drive the chambers to predetermined temperatures?

MAINS: Thermal control handles this. We have environmental chambers with the built-in control. The system does not interface to that. All we do is monitor the chambers and record the ambience and so forth. We do not try to control the chambers with the system.

HARKNESS: Do you mean to try to say we are trying to keep the pack at 20°C?

HENDEE: We have a test set-up at Telesec that was probably the most difficult thing to design, to be able to go out and to try for a simulation, to try the temperature of the packs, what they would actually see which isn't necessarily what the mounting shelf temperature is.

We drove in a closed loop system feeding back in. Then we got most of our memory with thermal control.

HARKNESS: Yes, that's right.

BOGNER: Bogner from JPL. Do you print out your data on a time base?

HARKNESS: We can ask for reports. We can get hard-copy reports as the pack is running. In other words, I can go

1h23

in and ask for a report, and I will get it right when it scans that pack. As far as getting the printouts, do you mean off the magnetic tape when the tape is done -- is this what you mean?

BOGNER: Do you record the data on a time base strictly?

HARKNESS: We record the data, every time that pack is scanned that data is recorded. That was built into the system. When we read the pack, we check it, and we have to check it to control it, so both of them go hand in hand, and the data is recorded at the same time.

BOGNER: You consider this having a printout based on the Delta lead?

HARKNESS: That is being incorporated this week. That program is being put in this week.

BOGNER: That will cut down on a lot.

HARKNESS: Right, and we will still have the capability to read it still every 2.4 minutes, but we will not record unless we do get a change, or an emergency limit or something like that.

GANDEL: Gandel, Lockheed. Are individual cell temperatures monitored?

HARKNESS: Only if required by Goddard. Normally, in a battery pack will read the first cell and the middle cell, at least the middle of the pack we will read with a temperature monitoring thermister.

GANDEL: How close do cell temperatures follow the chamber temperatures?

HARKNESS: If you are not running into any problem as far as excess of overcharge, or something like that, naturally it runs pretty close. I wouldn't say they differ more than one degree if we are not having any problems.

FORD: I would like to make a point here in clarifying the question, I think. I am not sure yet whether he got his question answered. We make no attempt to simulate a mixture profile in any of the cells that we test.

HENDEE: The point I was really trying to make is you are driving a plate, say, or your deck temperature, if your batteries do because of your management want to go higher you have a reverse effect. You are reffecting your mounting

1h24

surface temperature-wise, so as it is you cannot thermally just drive the mounting surface. In other words, what would be the deck, mounting deck, of the spacecraft. You must then, if your batteries want to go high, get again to speeding back and changing your deck temperature and you have to have a feedback in there if you want to do this.

My second question, I guess, is really how long are your average, would be your average test?

HARKNESS: Oh, I don't know. Five years, seven years. Something like this, maybe ten years.

HENDEE: I will talk to you later on.

FORD: The point is in the life testing, particularly in the project, we simulate the electrical profile that is predicted for the project. We are not testing flight units or even unit package flight cells. We are testing cells as a free component.

We keep the thermal conditions almost isothermal. We want to test the battery as you are indicating we would build a battery pack, put it on a data plate, and this is done on most projects. This is the life test of cells. To get the data relative to a temperature variation, we go the parametric route. We will bracket the temperature we are concerned with and put one in the middle, and then hope the information is sufficient to extrapolate the results. Just like that.

HENDEE: One comment. You did have several -- it looked like more than a dozen separate applications up there. That's all I want to say.

HALPERT: Thank you, Jim.

Despite Jim's pictures, NASA is moving in a forward direction, and this will be shown by our next speaker, Don Mains, who is going to talk about the design and preliminary test results from the accelerated test program.
(Slide 129a.)

MAINS: Thank you, Jerry.

You just heard that we do testing for five to ten years on some of these. This does get to be a long wait if you are looking for information, so we have been working, over the past few years. We have had a few preliminary reports on that. We are just about there right now, and I thought I would review a little bit of the design of the accelerated test that we are getting ready to set up at NAD/Crane.

This is in conjunction with NASA and the Air Force at Wright-Patterson Air Force Base.

1h25

Next slide.

(Slide 130.)

The objectives of the accelerated test are, one, to develop a nondestructive, predictive life test, where we will eventually be able to predict life, two, is to develop a simple screening program that can be used by spacecraft builders in the selection and matching of cells for flight batteries with a high confidence in the reliability of the batteries for that particular type and length of mission for which it is to be built.

This means if you are wanting a five-year battery or a three-year battery or a two-year battery you might buy one lot of cells and hopefully be able to screen and come up with batteries that would fit into these various categories.

And number three is to reduce the test time to a very small portion of the overall life, ultimately less than 1 percent. And four, to determine the degradation mechanisms through early removal of cells from life cycling.

The program started out with a very detailed study of the design factors going into the cells, the manufacture of the cells, the accumulation of the data at the manufacturer. This data has been placed on computerized data sheets, so that it will now be keypunched into computer format. We will then be able to analyze the manufacturer's data along with the baseline data that we will be taking prior to starting the test.

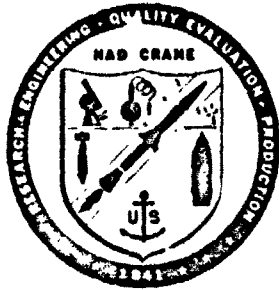
This is to give us some information as to what the cells look like when we get them from the manufacturer. We are already tearing the cells down some that have not received any cycling at our facility, and doing chemical analysis on them. This, then, will be used later in the postcycling test which will, again, look at what changes have occurred in the characteristics of the battery.

We will then go into the accelerated test itself, and then, as failures occur, the chemical analysis will be performed on those cells. We will be able to then correlate back to what the original cell looked like, what changes have occurred.

We also have in the program cells that will be removed periodically prior to failure, hopefully. We have at the present time designated three cells that will be moved, be removed at one-fourth the expected life, half, and three-quarters.

And, like I say, this is expected life we are predicting based on information that Dr. Landers has supplied to

BATTERY TESTING



AT



CRANE

FIGURE 129A

OBJECTIVE OF THE ACCELERATED TEST

1. Develop non-destructive test
2. Develop a simple screening test
3. Reduce test time (< 1%)
4. To determine degradation mechanism

FIGURE 130

1h26

us as to what the expected life is at the various conditions. Following the actual life cycling or the accelerated test then we will have statistical analysis performed on the testing to see what correlations, what information can be obtained, what acceleration rate, and anything else that might be in the data itself.

This is something that at the present time we are looking at several gaming techniques. We have statisticians at Crane looking at programs. We also have a consultant contract out with another group to do some evaluation along this line.

Next slide, please.

(Slide 131.)

This is the initial, or the final draft we came up with on the factors to be put into the program. The first five are electrical or environmental: the temperature, depth of discharge, charge rate, discharge rate, and percent of recharge. The last three are physical variables in the cells and were placed in by the manufacturer, and this is the concentration of the potassium hydroxide, the amount of potassium hydroxide, and the precharge.

The levels as indicated up there are -- we decided that five levels would give us a pretty good indication of how the variables affected the life. The configuration that we came up with is a factorial composite design. This allows us to have both the advantage of the factorial test and be able to come up with a much reduced size.

This particular test only involves 86 batteries. They are either five or eight cells, depending on whether we have the early removal cells in the battery itself. Once these levels were decided on, the test was designed, and I will not go through the total configuration, because 86 different temperature depth of discharge cross correlations would be quite tedious.

But the way the thing is designed, the level two and level four were used in a two-factor factorial design. And then based on statistical approaches, they thought we could get by with one-quarter representation, so that we have actually in that area one-fourth of what would be a two to the eight factorial test.

The other is the star point and center point. These are to allow the statistician to extend and to extrapolate the results, and these use levels one, three, and five, three being the center point level. Each of the other levels then are cross correlated to that.

1h27

After we got the design, and before we actually put a test on, we received some cells then. We decided it would probably be safe if we would do some evaluation to determine some of these effects, because some of them looked pretty far out and we weren't sure that they would work, and we didn't want to start out with a test and come up with a failure that we knew was going to happen right off.

So we picked out some of the more severe conditions to determine that temperature or pressure would not be the prime failure mode, because we felt that there were certain conditions here where we could blow the batteries up in a matter of a few days to a few weeks. We didn't want this to happen.

So the next slide is the first condition.

(Slide 132.)

We took 60 percent depth of discharge, 170 percent recharge at 20°C, and a charge rate of C and a discharge rate of 2 C. The number of cycles, we ran 20 cycles, mainly looking at the temperature and pressure to determine how they were behaving. And in this particular example you can see that they are either leveling out or showing a decreasing effect. So we are not going to run into thermal run-away problems or extremely high pressures.

Next slide, please.

(Slide 133.)

This was the next condition. Sixty percent, 60 percent depth of discharge, 170 percent recharge at 20°C, with a 2 C discharge rate, and this time a 4 C charge rate. And, as you can see, this is only two cycles: cycle 21 and 22.

We went into an overpressure condition and terminated both tests prior to the end of the charge period. As you can see, both the temperature and pressure were increasing on both cycles. We determined then that this condition would not perform satisfactorily.

It turns out that this was not one of the conditions in the matrix. We were hoping we could evaluate all of our combinations at 20°C.

The next slide, please.

(Slide 134.)

The actual condition that we would be running is at 40°C, so we moved the pack up to that temperature and

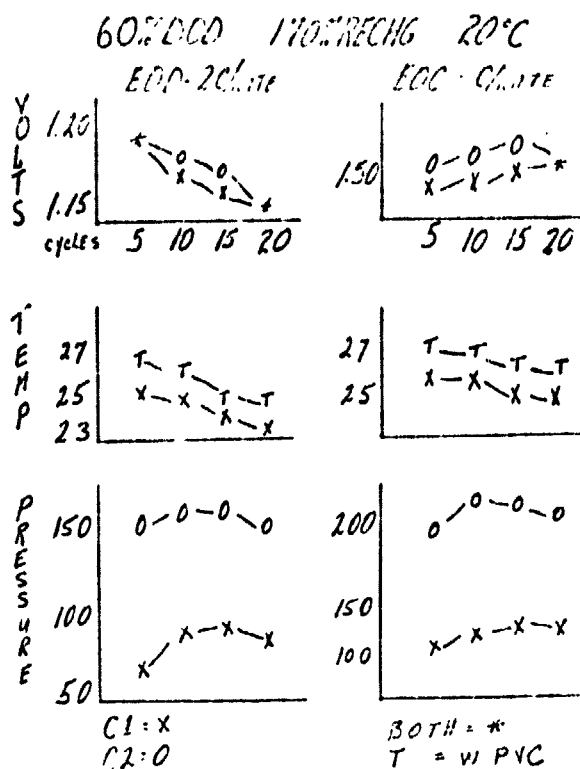


FIGURE 132

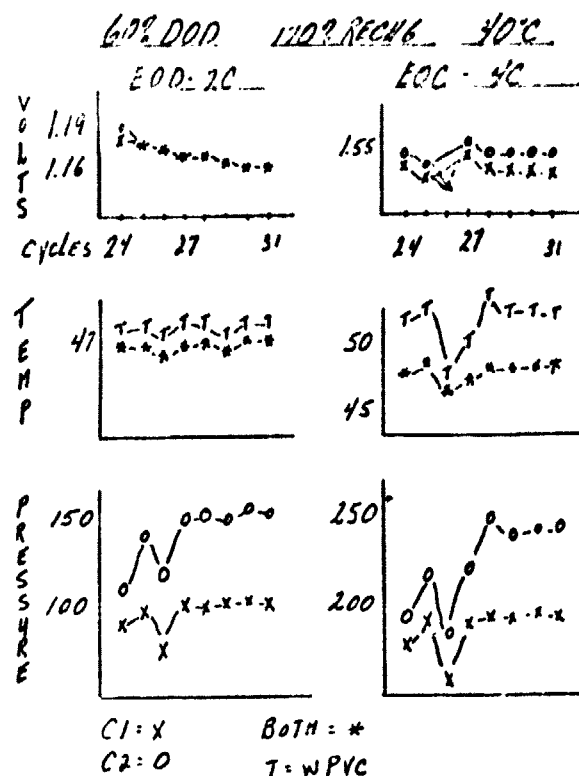


FIGURE 134

ACCELERATED TEST MATRIX 1

FACTORS	LEVELS				
	1 st	2 nd	3 rd	4 th	5 th
TEMPERATURE (°C)	20	30	40	50	60
DEPTH of Discharge (%)	20	40	60	80	100
CHARGE RATE (amps)	C/1	C/2	C	2C	4C
DISCHARGE RATE (amps)	C/2	C	2C	4C	8C
PERCENT RECHARGE (%)	110	140	170	200	230
CONCENTRATION of KOH (%)	2.2	2.6	3.0	3.4	3.8
AMOUNT of KOH (cc)	17.5	19.5	21.5	23.5	25.5
PRECHARGE (RH)	2.20	2.50	2.80	3.60	3.30

* STAR POINT
 ** FACTORIAL
 *** CENTER POINT

FIGURE 131

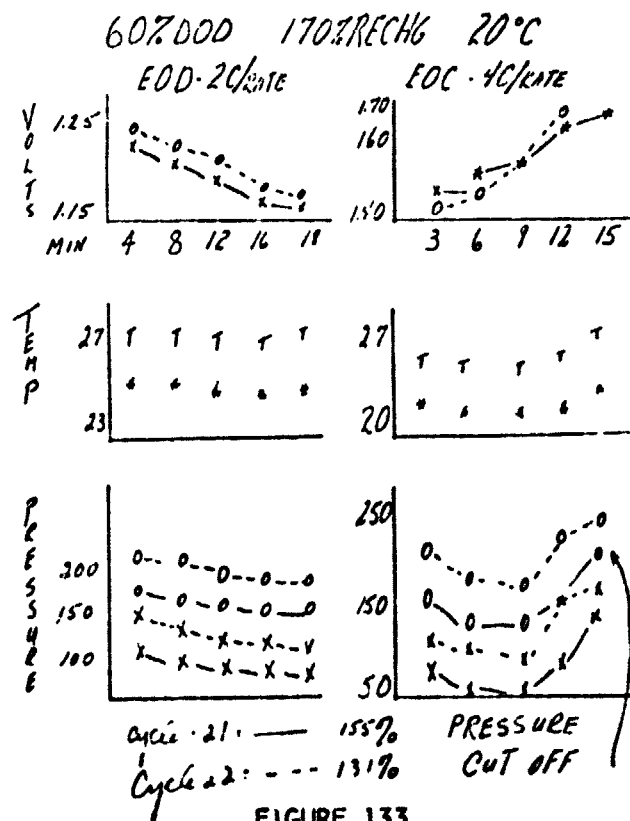


FIGURE 133

1h28

performed the cycling there. The temperatures and pressure did level out there, and operations appeared to be very stable. So we cycled for about seven cycles. Things were settling down. The one noticeable drop there is due to a temperature decrease on our chamber, so this is an indication of what effect the temperature does have on these particular packs.

Next slide, please.

(Slide 135.)

This one is at 60 D.D., 140 percent recharge at 40°C. Because the pressure had not totally stabilized out on the other one, we decided to decrease the percent of recharge to 140 percent. The performance was greatly improved and operations proceeded for about 30 cycles we were getting good level operations.

(Slide 135a.)

So then we moved on to our next condition. This one was at again 60 percent depth 140 percent recharge, 40°C with an 8 C discharge and a 1 C charge rate. Again, the operation here appeared to be pretty good. The temperature -- this is at 40° -- as you can see, the temperatures are running anywhere from about 5 to 10 degrees above the ambient. So at this time we changed plate size on the surface area of the plates.

We had been running with double size plates. We went to plates that were three times the surface area of a cell, and performance appeared to be dropping back down pressure and temperature started back down. So we went back then to the 20° test.

Next slide.

(Slide 136.)

Because we have changed the percent of recharge, we went back to the 20°C and reran the first test that we had performed. It still operated satisfactorily there, and we were pretty well what we thought would be all the testing we would do, but then we also noticed we had one temperature that was quite high.

(Slide 136a.)

On the next slide we have the performance at 60 percent, 140 percent recharge at 60°C, at 2 C discharge and 1 C charge rate. And here again the concern was that 140 percent would be sufficient to recharge the battery, and temperatures and pressures seemed to be fairly stable.

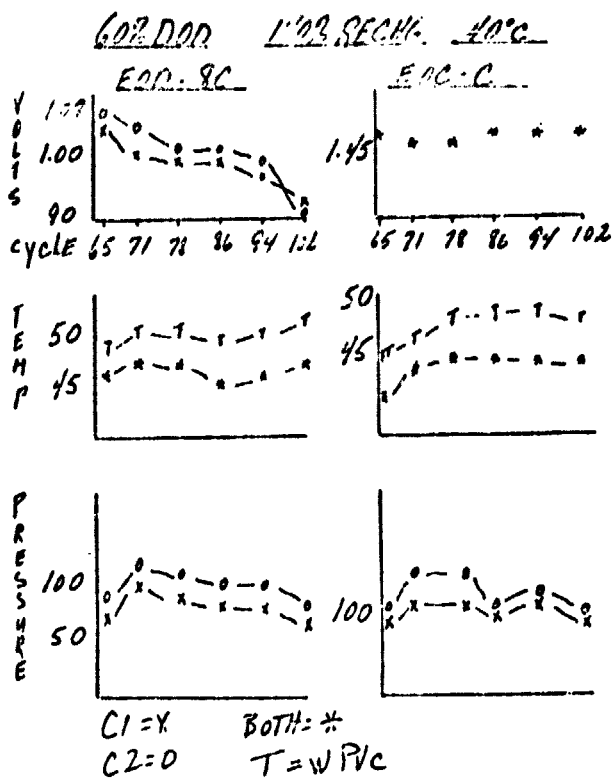


FIGURE 135A

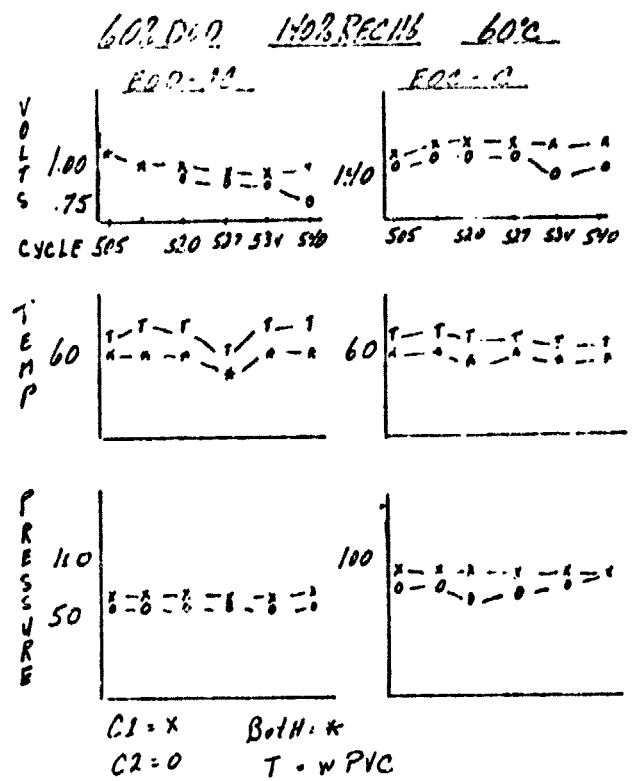


FIGURE 136A

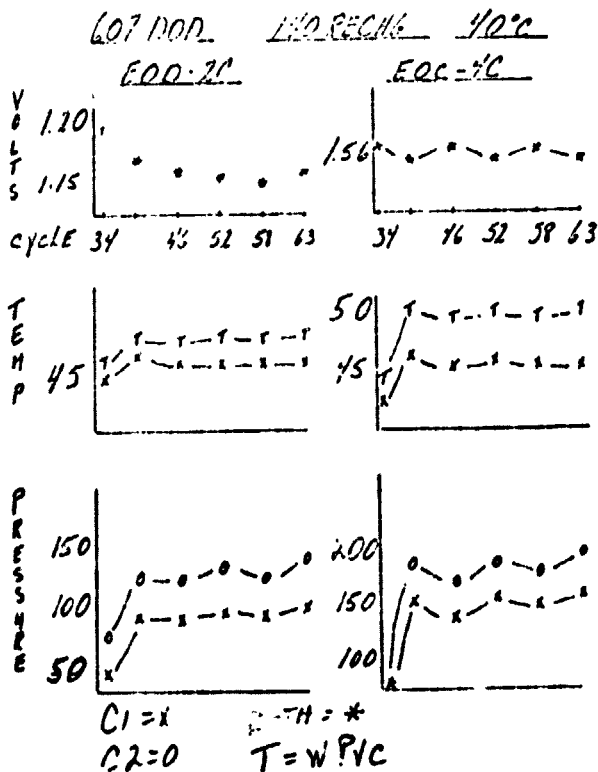


FIGURE 135

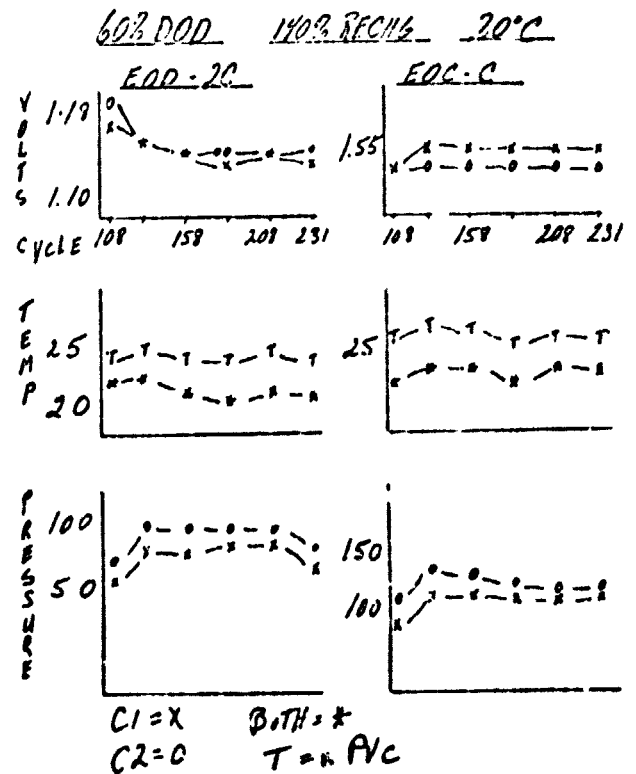


FIGURE 136

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We were operating right around 60°. Pressures are a little bit high, but they tend to remain stable. So, again, we thought this condition was fairly satisfactory.

Next slide.

(Slide 137.)

Because we had already adjusted our center point pre-charge down, we then tried to determine what the upper pre-charge would be, our maximum, our five-level precharge -- or percent of recharge would be. And on this particular test, we increased it to 170 percent. The performance again was stable.

Next slide.

(Slide 138.)

In the next slide we went to 200 percent recharge. We are showing some higher pressures here, and again, some higher temperature, but the operation overall is tending to be fairly stable so we feel that we can operate at this level. We have to get the percent of recharge up high enough so that we can see any effects it might cause. If we operate too low, then we can't have any information, that is, to what effect it would have.

(Slide 138a.)

Following all of these tests, we had one more check that we made. This was at 110 percent at 40°C. This was our low limit, and we felt fairly confident that it would work, but again, knowing how nickel cadmium cells are, we didn't want to take a chance and say, well, it just absolutely will run there.

So we ran it for about 50 cycles. Everything was pretty well stable: the temperature, the pressures were down, and the battery performance was operating pretty well. So we feel that this condition will also operate satisfactorily.

Next slide.

Following this test, we had -- we have a slide out of sequence. Oh, wait a minute. He doesn't have the slide. Okay. But after this test was completed, we had two cells that we had been working with. We didn't feel we want to put them into the regular configuration, so we then started them on what we a life cycle, the conditions being 60 percent depth of discharge, 140 percent recharge, and 40°C, and a 2 C discharge and 1 C charge rate.

1h30

The anticipated life is around a thousand cycles, and at the moment we have completed 700 additional cycles at this condition. And the performance right now appears to be doing pretty good. We have an end of discharge voltage of about 1.7 volts, end of charge voltage of around 1.51, and pressures in the vicinity of 70 to 80 pounds. So it seems to be operating pretty well.

(Slide 139.)

This is now the revised version of the text matrix, that we will be implementing at Crane, and, as I have indicated, the factorial level will be determined when the lot two cells come in. Because of the expense of this, we had to go to two lots of cells.

Next slide, please.

(Slide 140.)

This is our time schedule as to when we hope to have the tests on and in operation. We are already underway in fabricating the packs now that determine the size plate we feel we need. Each cell will have temperature monitoring against the cell scan itself.

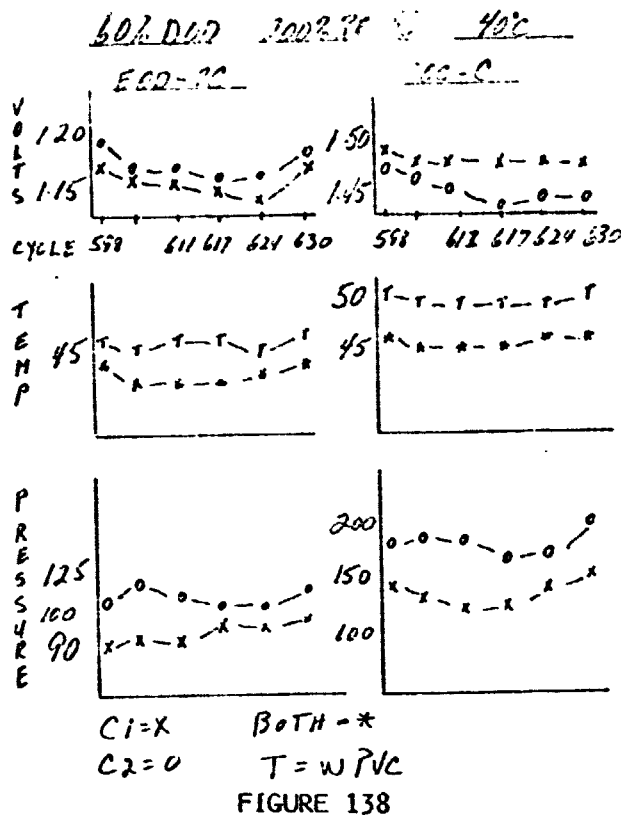
Within the next few weeks we will have completed our baseline test and be starting into the cycling conditions. And hopefully then, maybe next year we can come up here and give you some answers on accelerated testing, what is a good test or a bad test, at least give you some additional information of that type.

Thank you.

GANDEL: In looking at your variables, it seems that all of them except one you seem to span reasonable ranges, expected ranges of operation. But in temperature, working from your 20 to 60, you are working above the range most of us are planning on using. So, when you are all through and you begin analyzing the data, then you won't be able to have temperature dropping out of your real variables.

Now, if you had, if you skewed the temperature and maybe go minus 20 and maybe stop at plus 30, because I don't think reasonably you would want to design a system above 30, then in exercising the other variables you might come back and end up with your temperature data giving you something meaningful.

I understand your temperature is the biggest driver in setting up accelerated tests; maybe you could still throw one temperature at a low end, and maybe that will make everything last for ten years. But still, it might balance it. Have I made myself clear?

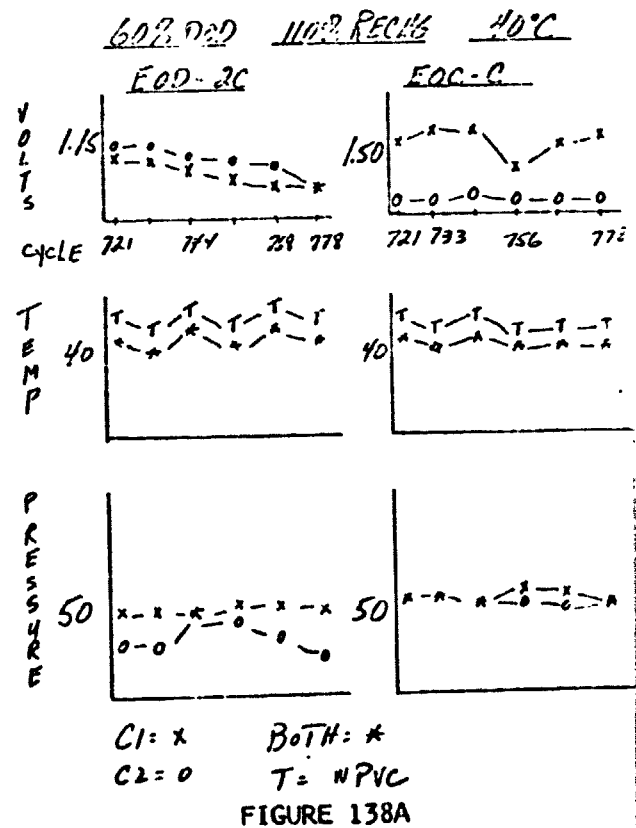
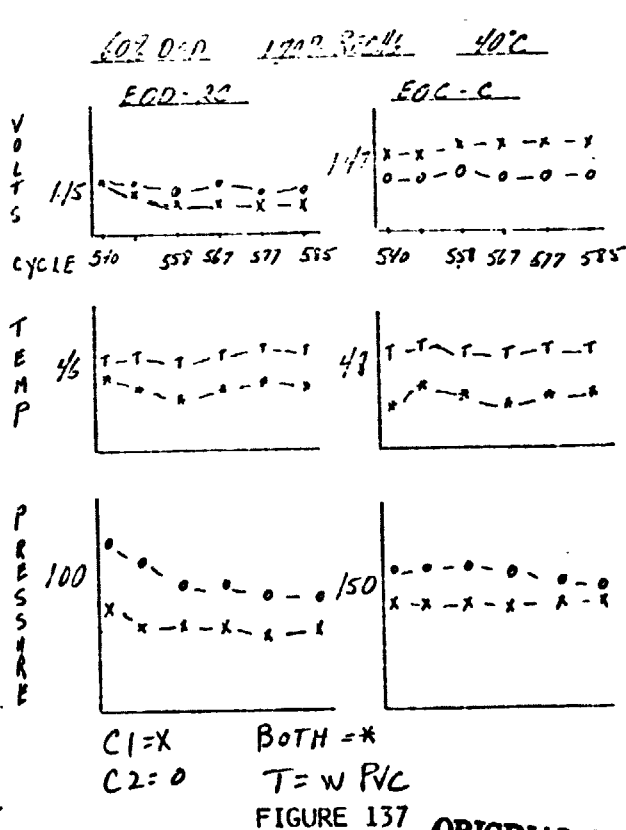


ACCELERATED TEST MATRIX II

FACTORS	LEVELS				
	1	2	3	4	5
TEMPERATURE (°C)	20	30	40	50	60
DEPTH OF DISCHARGE (%)	20	40	60	80	100
CHARGE RATE (AMPS)	C/4	C/2	C	2C	4C
DISCHARGE RATE (AMPS)	C/2	C	2C	4C	6C
PERCENT RECHARGE (%)	110	*	110	*	110
CONCENTRATION OF KOH (%)	22	26	30	34	38
AMOUNT OF KOH (cc)	17.5	18.5	19.5	20.5	21.5
PRECISION (AM)	1.20	2.50	2.80	3.00	3.5

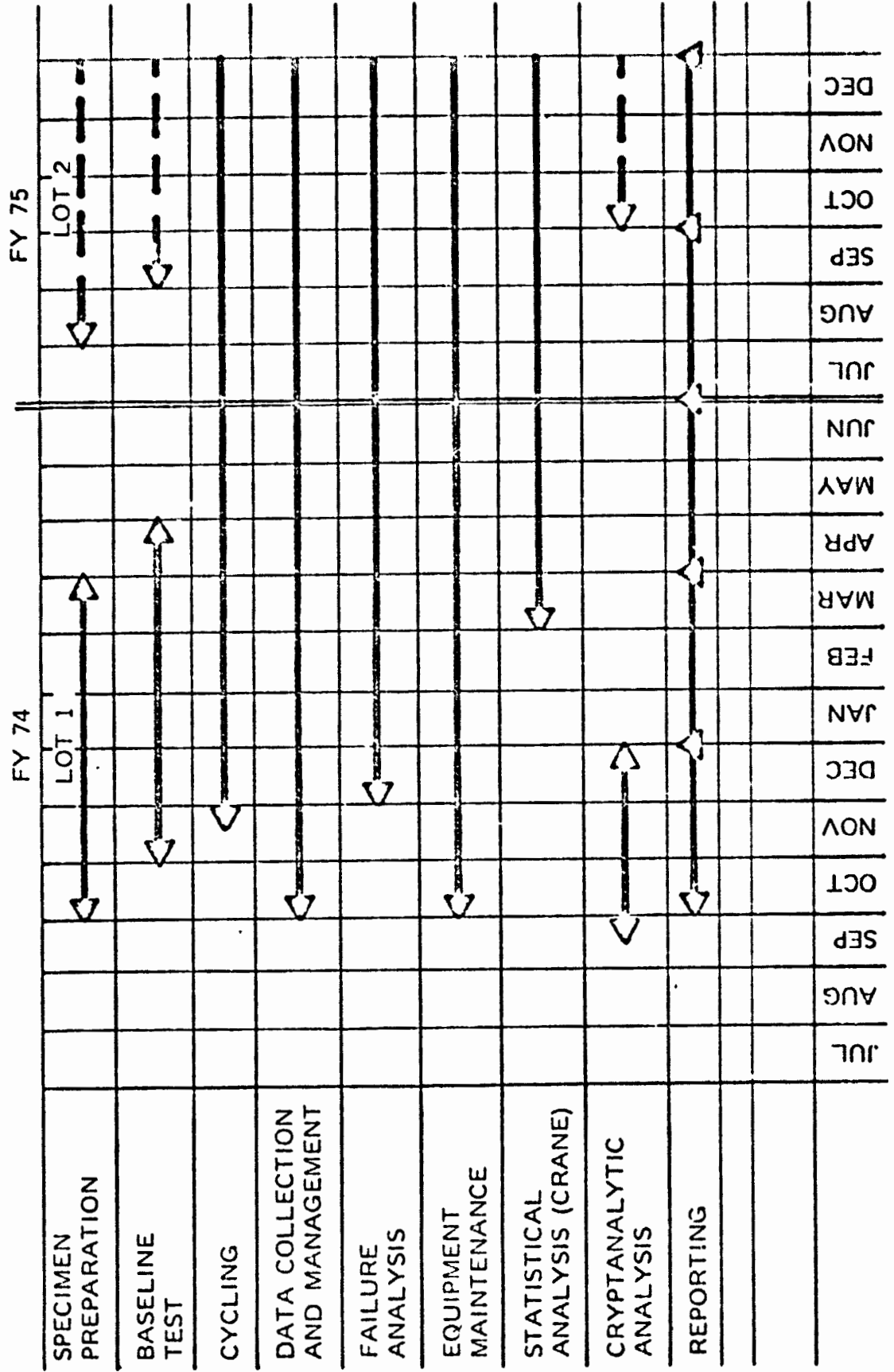
* TO BE DETERMINED ON LOT #2

FIGURE 139



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MILESTONE SCHEDULE ACCELERATED TEST PROGRAM



1h31

MAINS: Yes. This was one problem that we had when we first set up the test, that was to, first of all, set it up into the normal operating ranges and get life. What we are trying to do here is to accelerate this to a very extreme condition, and we felt that high temperature was one of the conditions that we wanted to go to.

In answer to being able to come back to real time data, we have what we call a normal test that will be following this, operating at 0 and 20°C of the same type cells and that, so we hopefully will be able to correlate back into -- those will last ten years, to show ten years' performance.

But we are hoping that this 60-degree will give us an idea that if you buy a lot of cells, and you want to find out are they good or bad, you can do it in a week's time with something like this. Run them at 60 degrees, look at your information, apply the statistical manipulations that are needed on the data, and predict out at 20°C or at 0°C I am going to have 10, 15, 20 years' life.

But we thought we had to go to the higher temperature, because this is one of the greatest accelerating factors that we could see.

FONT: You have tested high temperatures but in different projects you can design that cell. At low temperature we can meet this specification. I can, I am quite sure, so I would like to know how you conciliate these two things.

MAINS: I didn't quite catch your question.

FONT: You can have cells that you design for low temperature operation for long life. So perhaps you will design these cells with low temperature. If you test these cells at high temperatures, 40°C, as you have a low charge, the performance will be less than it would be designed for high temperature.

How do you make the correlation between the quality of the cells at high temperature and quality of the cells for low temperature application?

MAINS: This is one reason we introduced the three physical variables in the cell, to try to determine the effect of precharge, the amount of electrolyte, and the concentration of electrolyte on the cell. Now of course, this doesn't say that, okay, if you specifically design for low temperature how will it operate at high temperature.

FONT: What is the range of recharge that you have, because it seems to be very close? You have a maximum of 3.3. What is the maximum precharging, the capability on precharging these cells? What is the excess?

MAINS: These are 6 ampere-hour cells.

1h32

FONT: So 3.3 represents what percent of this excess -- 80 percent?

MAINS: I am not certain.

FORD: What he is asking is what is the total negative capacity of the cell.

FONT: If you express the percentage of your excess, what is your range?

HENNIGAN: It is about 13 ampere hours.

LURIE: I think the whole question of the levels of variables is a very tricky one from the point of view of doing a useful experiment. Because obviously from the experimental design that is chosen they intend to come up with a series of regression equations, which are going to bind these variables together.

And unless your variables extend a little bit beyond the useful range at both ends, you are in danger of getting a regression expansion, which is not really going to be valid right at the very end.

So I think most statisticians will tell you they would like to see, in a five level experiment like this, the two extreme ends of the variable range. perhaps push fairly hard against what you think your useful range is in order to get the maximum reliability -- maximum reliability in the regression expressions, which are in fact the net results of this whole program.

MAINS: As I understand it, this is pretty much what these levels are doing, these physical levels.

LURIE: That is not only correct, I think it's absolutely necessary, especially because you are going to a fractional design. And when you go to a fractional, a quarter design like that, your ability to state that this is a correct regression expression, it just becomes more -- as the fraction gets smaller and smaller it becomes more and more difficult to talk about the statistical reliability of your regression.

MAINS: Yes.

HARSCH: Harsch, Eagle Picher. I want to say one more thing about the temperature. I think most of us that have tried to set up accelerated test programs have used temperature. I think everybody tends to want to go towards the high inner temperature. It has been my experience, what happens

1h33

when you run these tests, temperature no longer becomes an accelerated factor but the predominant factor. It overshadows all of the other variables you had in the program.

So when you go to analyze the data, you are not really seeing true conditions. You are seeing the effects of temperature rather than the effects of any other variable you put into it.

MAINS: The test that we outlined here only covered a small portion of it. There will be a considerable amount of testing at the other temperatures with cross correlation of the other parameters, so that hopefully not only temperature but depth of discharge, recharge rate, discharge rate, all these will be correlatable on our two level effect.

HARSCH: I am talking primarily about the test matrix you showed here. All of your temperatures are at the high end, so I would say that the only data that we could hold on to would be the tests run at 20°C. From there on up it is going to be shadowed by temperature.

MAINS: As far as direct correlation to usefulness, yes. This is an area we ran into, again trying to look at accelerated and to look at useful tests. We didn't want the tests to run five to ten years, because that's what we have now. We've got to get something that will kill it off quick, but will kill it off in a mode that will be similar to what we normally expect.

Like I said, when we first started we didn't want to blow the cells up, which we could do.

HARSCH: As a manufacturer, it's very bad when you run a test like this, and then come back and tell us your cell isn't going to make ten years because you tested it at 60°C.

MAINS: I don't expect some of these to last more than two or three months.

HARSCH: Right. But you are going to predict.

MAINS: Hopefully then, with all the testing and with the normal sets we will have in there to correlate back what actual 20-year life is or 10-year life is on this particular cell.

HARSCH: I just wanted to make the point. Perhaps if you see the whole matrix it might look different.

SHULMAN: Joe Shulman, Pace Center Systems. I would like to understand how you are dividing up groups of

1h34

cells. Do you divide up into five groups, one group for each one of your columns -- how are you dividing it up?

MAINS: Like I said, it was 86 packs in the test. You have to really see the whole matrix to understand exactly what the parameters are. but there will be a minimum of five cells at a given test combination. And there can be as many as eight, if they have the three early removal cells.

So that there will be a report out very shortly. It is in the printing now, a NASA report, that outlines the complete matrix. And, like I say, it does cover 86 test combinations.

GASTON: I assume all the cells are from one lot, the same separator lot, the same plate lot -- is my impression wrong?

MAINS: There will be two lots. The Starpoint and Centerpoint test and normal test will all be run from one lot. The factorial test will be run from the second lot. There will be some cross correlation there to try to determine if we have had any major variable changes or anything like this. This was something that we had no control over. We had to go back for a re-order to get additional cells to complete the expanded test.

STEINHAUR: How do you plan to accommodate the problem in a general sense -- the temperature question has been raised, but in a general sense are you dealing with the same failure patterns or not?

MAINS: I am not sure we have an answer on that yet. We are going to have to see what the results are and hopefully come back and see if this is something we can really predict on or not.

DUNLOP: Just to augment that question a bit, there was a fair amount of data presented yesterday on real time testing by Hughes and myself. And it was interesting to note that many of the variables you have are included. And, of course, the major mechanism that caused all of the deviations -- and that's a synchronous application -- was the storage mode.

The point here really is the kinetics there are obviously much different than anything you are going to come up with in this test. I would have an impossible time selling anybody in my project office a failure mechanism based on 60°C as a criteria for saving that particular cell was a good or bad design for an INTELSAT mission.

lh35

I guess, in a way, the problem I really don't understand -- this is like saying you don't know anything about nickel-cadmium cells, so you have to start a massive program to look at everything. Frankly, you know a great deal about nickel-cadmium cells. I am not really sure why you don't zero in more on what you are really trying to identify as far as mechanisms are concerned, such a broad based thing

LACKNER: Joe Jackner, Defence Research Establishment. I think people are talking around the common point here. In the design of your tests people are saying we are worried about high temperature, and we are worried about failure mechanism.

Now, we do know that -- well, at DRE we have done some tests for NASA Goddard because we are quite concerned with high temperature, that is you want to operate at high temperature you are worried about your charge efficiency. Now, the charge efficiency is improved by charging at a high rate, and you design all your tests to charge at a high rate.

I appreciate your trying to accelerate this, but, believe me, if you wanted to accelerate it, charge at plus 40 to C/20 or C/10, and you will find that the results will be very poor very fast, because your charge efficiency is not very good. You've got to get at least 1.40 volts to charge efficiently. And all your voltages there are way above 1.40. They are 1.5, 1.50.

In effect, you are not testing high temperature, because you are testing it at the most favorable conditions. So you shouldn't really put in there lower charge rates if you want to get the high temperature failure mechanism.

HENNIGAN: We know these low charge rates will fail to show it in a short time, but it really didn't fail. You can bring it down to 20°C and operate the cell again because of the charge efficiency. What we were trying to do in the initial test was to get a charge rate that would keep the capacity of the cell up and not have to take the cell out in the first two or three cycles because of pressure.

That cell hasn't failed yet. You could stop the test, bring it down to room temperature and still run it. We want to get the shorting modes and separator going, the cadmium migration and so forth. True, all of these conditions are not practical because of the synchronous orbit, and at times we are running some that won't match the 90 degree 100 orbit.

We are just trying to get a tool here to take a lot of cells and to test them to see if the manufacturer put out

1h36

a good lot. This has been our problem for years, to determine whether the lot was good.

LACKNER: In that regard, perhaps you should establish a guideline with the manufacturers. Several of them have said that they have various treatments that will allow them to operate their cells at high temperatures. If you can get plates that have this and move them through the test and have a correlation there, I think you will come up with something useful.

HENNIGAN: These have the treatment.

LANDER: If that statement is correct, I would like the two manufacturers who supply aircraft batteries to come around and talk to me. I am Lander from Air Force.

TAYLOR: Taylor, McDonnell Douglas. All of these are in five cell packs, right?

MAINS: Right.

TAYLOR: Have you ever considered doing one cell by itself as a control or a baseline?

MAINS: As far as the overall tests?

TAYLOR: At the various parameters, the matrix.

MAINS: Well, the feeling was that five would really be a minimum to give us statistical analysis and be significant. The reason for doing one, we would just have to repeat it with a larger group later. This is the reason why we did it with this two cell group, was to try and at least overall get a quick view of how would the performance pan out.

Because we have talked for a long time, we have discussed the matrix with a lot of people, both users, manufacturers, and so forth, to try to come up with the levels we have here. And they are not realistic use levels. This is one thing that is kind of hard to accept when you first start in on this, but we are trying to accelerate, trying to fail this thing early.

The only question we don't know is will it fail for the same reason on these tests as it would at 20 degrees in ten years, and this is something we are trying to prove. I mean we don't know.

TAYLOR: The reason I was asking was are you using one cell out of the five as a control on charge cutoff?

MAINS: No. As far as control, we are charging at a fixed rate to a fixed percent of recharge, no voltage limit,

1h37

pressure, yes, we're going to cut off before the thing blows up, and that's about it. The idea is to take them to failure and failure will be zero volts.

MR. LURIE: I think there is a feeling, when one looks at a large factorial experiment, star experiment of this type, you are assuming you don't know very much about the system. And there is a temptation to look at individual failure mechanisms, making use of background that you already have.

In defense of this method, the system is clearly very highly interactive, and these variables all interact with each other. They interact very strongly. This is definitely the most reliable way of getting to those interactions without doing literally thousands and thousands of experiments.

I think there is a very real danger of not seeing those interactions unless you approach it from this point of view.

MAINS: Right. I think this is the main thrust of what we were after; trying to leave ourselves open to a certain degree to look at everything, but not to come up with about 3,000, or something like this, batteries that would have been needed to run this type of a full matrix.

HALPERT: I think that's a good note to end on. At this point we will continue by having some coffee.

(Whereupon, a short recess was taken.)

tp 1(2)

HALPERT: Well, we have talked a little bit this morning about experimental set-up, experimental design, and then we talked about a program for accelerated testing. Our next speaker is going to follow along in a similar vein that is John Lander from Wright Patterson Air Force Base who is going to talk about cycle life prediction based on modeling. John Lander.

LANDER: Would you put the first viewgraph on, please?

That's the title of this talk, and this work is part of the effort that was just described by Don Mains. And Harry Seiger yesterday showed us physical chemo plaque to draw straight lines, and I think you will see that as this develops.

Also, regarding the conversation we had about temperatures, the users would like relief from that temperature

1h38

situation, because we have to put a lot of effort on those batteries to make them work. All right? Okay. In NiCd cell cycle life testing, the most commonly used factors for acceleration of degradation of failure have been increase of depth of discharge and temperature.

We shall proceed here to illustrate how these might be used to define and predict cycle life from accelerated testing by using these two factors, and this is really a kind of simple approach to this overall problem. And I just worked it out to see how it would work out based on the available information that we have, and we will show you how it does in the course of the talk.

And to show you how simple this is, we are only using two assumptions. The first one is that the degradation rate is a linear fraction of the depth of discharge and it passes through the origin, that is, it's zero degradation at zero depth of discharge.

The second is that the degradation rate doubles for each 10°C , 18°F rise in temperature. Now, this is a commonly used rule of thumb in chemistry to affect the temperature effect, to express the temperature effect, on chemical reaction rates, but like rules of thumb, it's not always very accurate. Anyway, we used it for the first approach, and its lack of accuracy isn't of any particular concern for building the model.

Now, it's going to be of concern when we attempt to refine it and try to predict life. Also, we shall arbitrarily select the degradation rate to be 3 percent of capacity loss per thousand cycles for the test conditions, 50 percent depth of discharge and 50°F .

Now, when we take these two assumptions, we get a family of curves which will be on the next slide, I think. Oh, let's hold that for a moment, and give us the first set of -- all right.

(Slide 142.)

These curves are automatically defined by those two assumptions in the arbitrary selection of the 3 percent per thousand cycles, which is the circle on the lower curve. You can take that off. Now, those curves which I just showed you can be used to establish a set of life curves as a function of depth of discharge and temperature in the following way. That's what they can be used to establish.

Now let me talk -- would you put the first graph back on? I will talk about that for a moment.

(Slide 142.)

1h39

We can use these to establish the center curve, which was just shown, and the way you can do it it's a simple procedure -- arithmatically it's this way. Suppose, for instance, you take the condition 75 percent depth of discharge and 50°F. The degradation rate from this set of curves is 4.6 percent per thousand cycles.

Now failure occurs when the cell can no longer deliver 75 percent of its rated capacity. So that means that the cell can lose 25 percent capacity before failure. If we divide 25 percent by 4.6 percent and multiply by 1000, because it's 4.6 per 1000 cycles, we come up with the cycle life of 5,440 cycles.

You can do that for any other condition which is described by these curves. And if you do so, then you come up with a table of values which we can plot in the set of curves which was shown here. And you can see that the curves kind of look hyperbolic. I don't know whether they are really hyperboles or not. We will tell you what they are in a few minutes.

Now, instead of doing this arithmatically, we can derive a mathematically exact equation for it.

(Slide 144.)

Oh, that's what I just told you. We can do this arithmatically or we can derive a mathematical equation.

Let's have the next slide, please.

(Slide 145.)

The cycle life is the allowable percent degradation divided by the degradation rate times a thousand, because the degradation rate is percentage per thousand cycles. And the allowable percent degradation, as we said, is 100 minus the depth of discharge.

Now, by our first assumption, the degradation rate is a linear function of the depth of discharge with a slope down depending on temperature. And by our second assumption, the increase on that slope, where M_1 is the 50 degree temperature, is expressed by two times the exponent of T minus 50 over 18.

It's easy enough to derive that based on that assumption. So then the degradation rate is equal to, for 50 degrees -- well, any temperature sequel to M , not M prime -- times two to the exponent, T minus 50, over 18, times the percentage of the discharge.

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FIGURE 141 NOT AVAILABLE

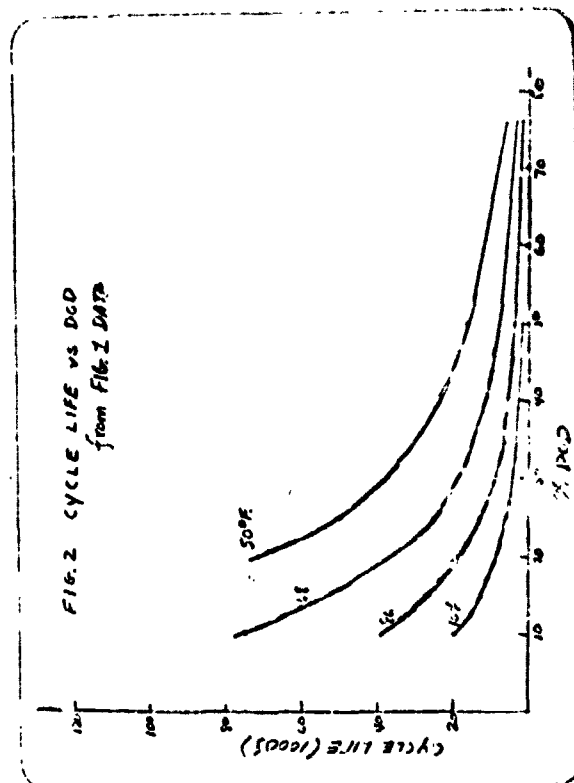
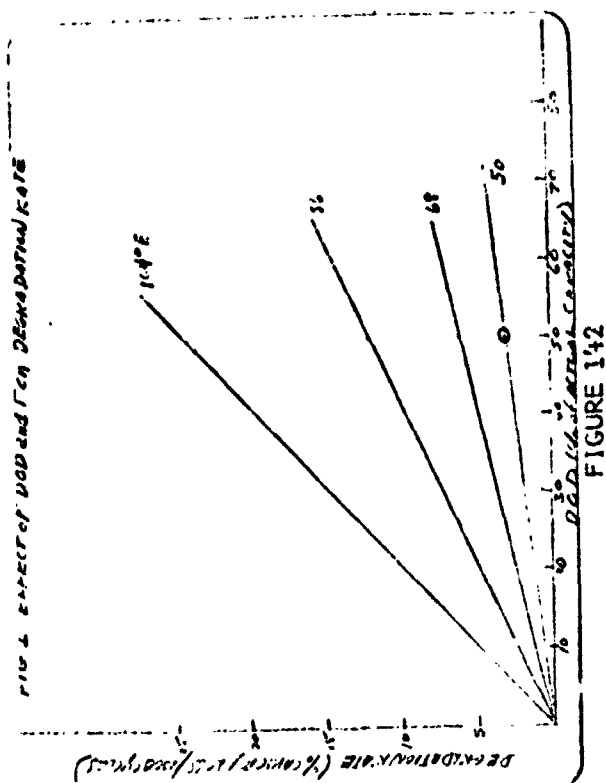


FIGURE 143 NOT AVAILABLE

1h40

So if we substitute that expression into the first equation, rearrange it a little bit, you come up with the cycle life divided by a thousand equal to $1 \text{ over } M \text{ times } 2$ to the exponent, $T \text{ minus } 50 \text{ over } 18$, times 100, minus the percent of the discharge over the percent of discharge.

And we have arbitrarily selected M prime to be .06 for 50 percent depth of discharge and 50 degrees Fahrenheit. Okay, that's mathematically exact. And looking at the right-hand side of that equation, you see that the equation, the cycle life on this basis, is a function of two power series which multiply one another, which explains the shape of the curves that we have already seen.

Now, how good is this model? If we can have the next graph.

(Slide 146.)

Here is a model with experimental data which was taken from NASA Special Publication 172, and these cells were manufactured around 1960, and they were tested at what used to be Cook Electric, which is no more.

The upper two curves are graphs from our model, the lower curve is experimental data from approximately 1960's test work for 75 degrees. Well, looking at it you say, well, the shape of the curves of the model may not be too bad. They are certainly too high, based on this information. So let's look around a little bit more

There is a later study, which was made by the Royal Aircraft Establishment, which was reported in 1967 by Garrett and Pomroy, on the effects of depth of discharge and temperature on a 90-minute automatic cycle. From their capacity curves, they -- oh, they measured capacity on this cycle routine.

The conditions that they used first were depth of discharge ranging from 5 to 50 percent and two temperatures, 0°C and 20°C , which are 32 and 68 Fahrenheit, and they checked capacities during the cycle routine. They had three, six, and 12 months. I believe that test was continued, but I don't have any later information on it. I wish I did.

Now, the cells that were used in this test were Gulton cells and they were probably manufactured back around 1964 or 1965, based on the test report date and the time that the testing had gone on. And from their data, I have constructed a table which relates percent energy loss on cycling as a function of depth of discharge and temperature or the two temperatures concerned.

1h41

I don't have a graph showing this, but we do see this data in the next figure. Oh, not that one. That's -- no, the next set of life curves. Yes, that's the one we want.

(Slide 147.)

Now, this curve shows the Royal Aircraft Establishment data for 68 degrees versus our model, F 68°, and it also shows the older electric company data. Now, we look at those, and we say, all right, our model isn't looking bad based on curve shape anyway.

It still indicates a little better life than was obtained by either the Cook Electric or the RAE data, but there is another thing we can say about those, that information, also. And that is that during the intervening years between the time the cells were built for Cook Electric and they were built for Royal Aircraft Establishment there has been a very nice gain in performance. Okay.

Now let's go back and take those ones which we skipped over.

(Slide 148.)

This plots the Royal Aircraft Establishment data, some of it anyway, for 32° and 68° as a function of percent depth of discharge. And we also culled out of the old Cook Electric data some higher temperature points. Now, I wouldn't look at those curves and say they are straight lines. But regardless of that, we drew straight lines anyway, because it's really not a bad fit.

But anyway, we used these list data to construct the life curves which we have just shown you.

Now, we have changed things a little bit. We have gone from capacity degradation to energy degradation now because we had the actual capacity discharge curves to work with. Also, we can now get a better figure for the slope M of the degradation rate curves.

And if you'll -- oh, okay. We took that data and smoothed it and said this was it. Now let's go one more

(Slide 149.)

All right. There's a curve which -- subfile line -- there it is. This, taking that last set of curves, we can plot the log of M over M prime as a function of the temperature, the temperature function, and from that we can draw a line through there and determine N. N is the power to which the temperature function is then raised in our equation.

FIG. 3 Comparison of model with experimental data

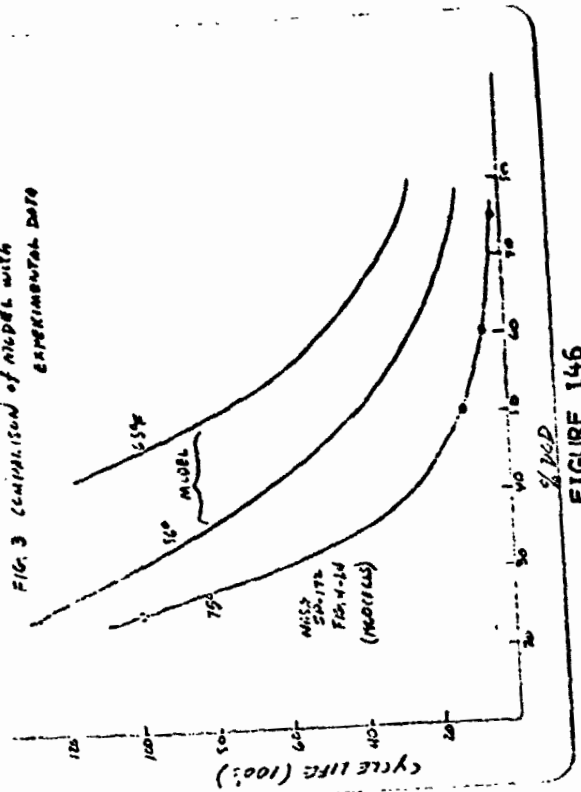


FIGURE 146

FIG. 5 DEGRADATION RATE VS DOD FROM FIG. 4 DATA

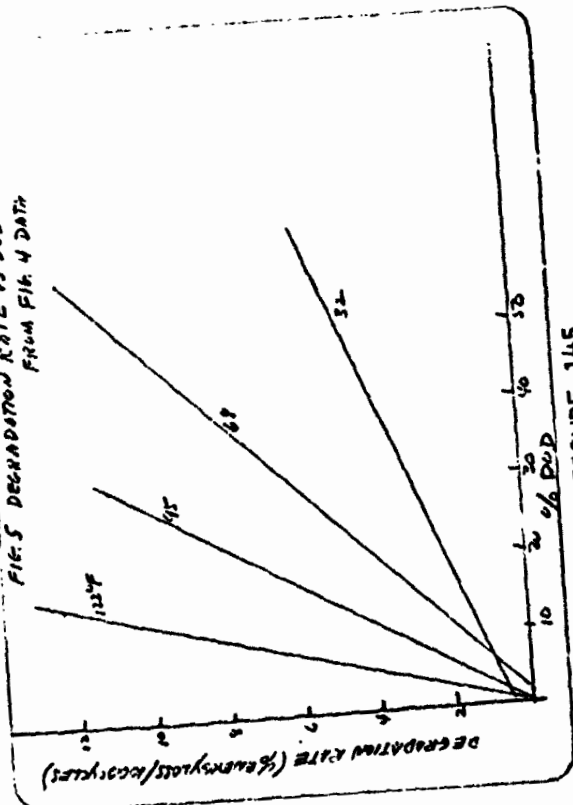


FIGURE 145

FIG. 7 CYCLE LIFE VS DOD: IDEAL DATA VS CUR MODEL

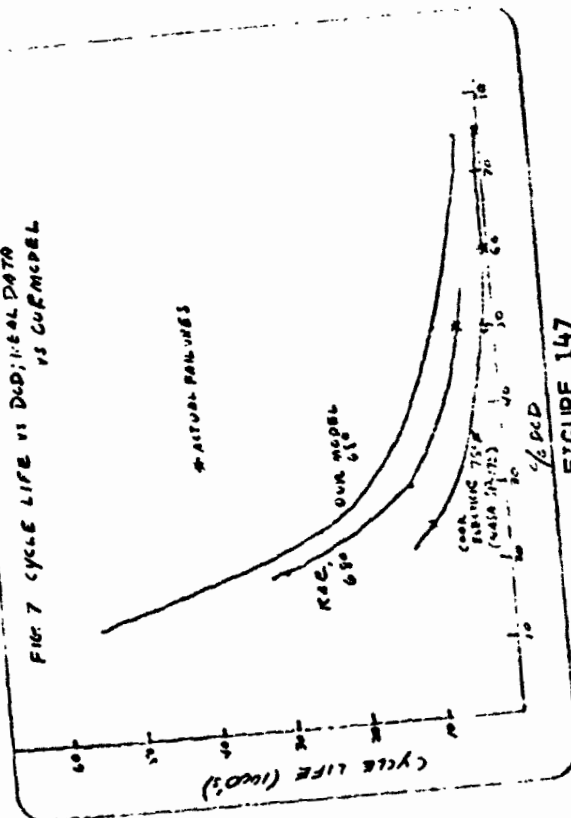


FIGURE 147

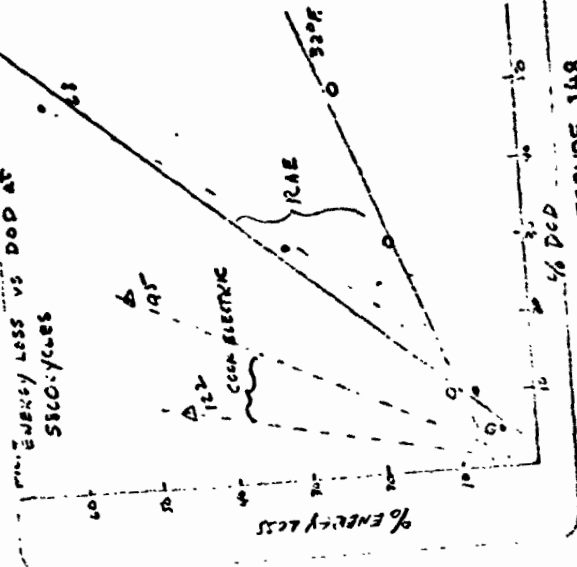


FIGURE 148

1h42

And for this data from RAE, in RAE, I am using the old Cook electric data: we come up with a value which is 1.52. This says now that the temperature effect doesn't double degradation rate with every 18 degrees rise in temperature, but it goes up as a factor of 1.52 per 18 degrees temperature rise.

So that's the first correction to our basic model. Okay. Now we still have more recent and better information which is deriving from tests which are currently underway at NAD/Crane for cells which were manufactured by Gulton in 1966.

Now let's have the next one

(Slide 150.)

And from that most recent information we can now plot the NAD/Crane data for 68° against our model. And also we have included the RAE and the older NASA data. And again, the shape of the curve model looks pretty good versus the available information, which is really quite spotty, so we will say okay, it looks pretty good, so far.

Also, you can see from comparison of the RAE data and the most recent Crane data that another nice jump in performance has been achieved. Now, we can use this most recent data also to re-correct the value of the slope of our degradation curve.

Now, it turns out that if we use the value for the power which the -- the number is raised to the power T minus 50 over 18 -- it turns out to be 1.45, which was a little too different from the 1.52 which we got on a basis with the RAE data. So we will settle on saying 1.50 as being a reasonable number based on the information we have at hand.

So let us proceed then.

We will reconstruct our model. We won't change the nature of our basic assumptions. We will go to -- we will use 1.5 as the number which has to be raised to the power expressed in the temperature, and will use the most recent experimental data from the 1966 Gulton cells of 6500 cycles to failure at 68° and 60 percent depth of discharge. And that gives us a basic degradation rate value for those conditions of 6.1 percent per thousand cycles.

And if we can see the next.

(Slide 152.)

And that gives us these degradation rate curves as a function of depth of discharge and temperature, and the star

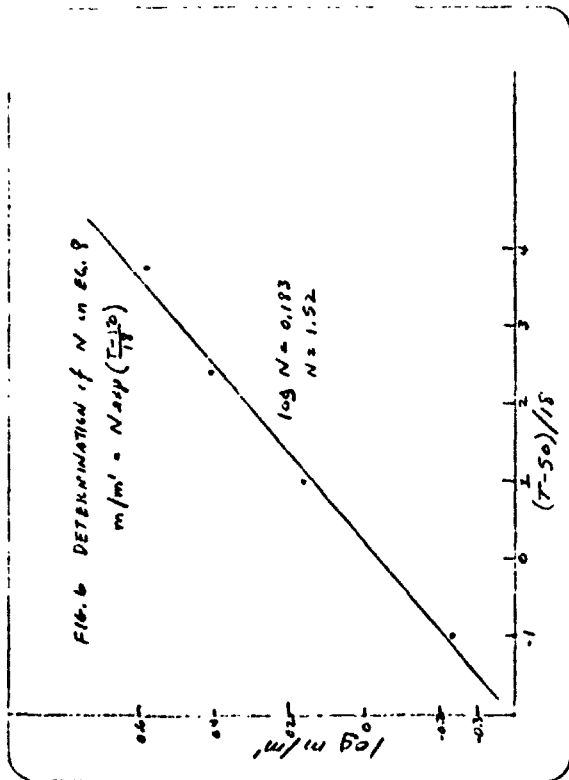


FIGURE 149

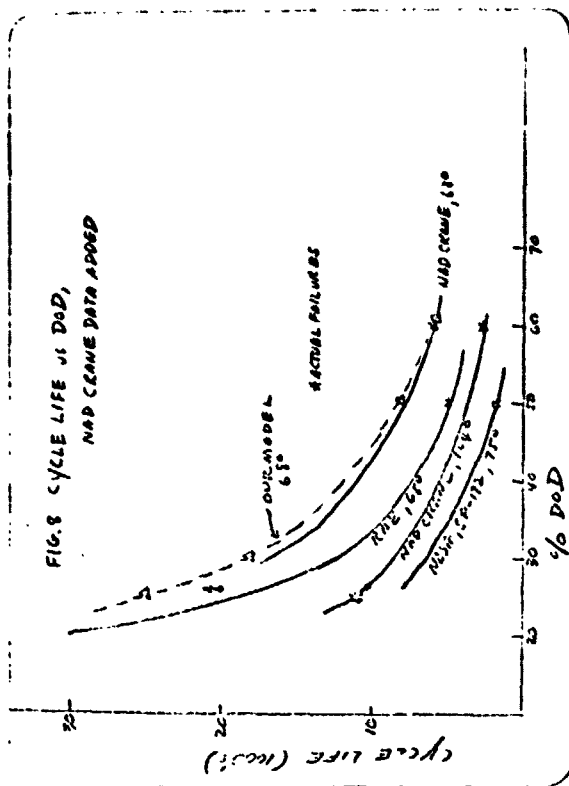


FIGURE 150

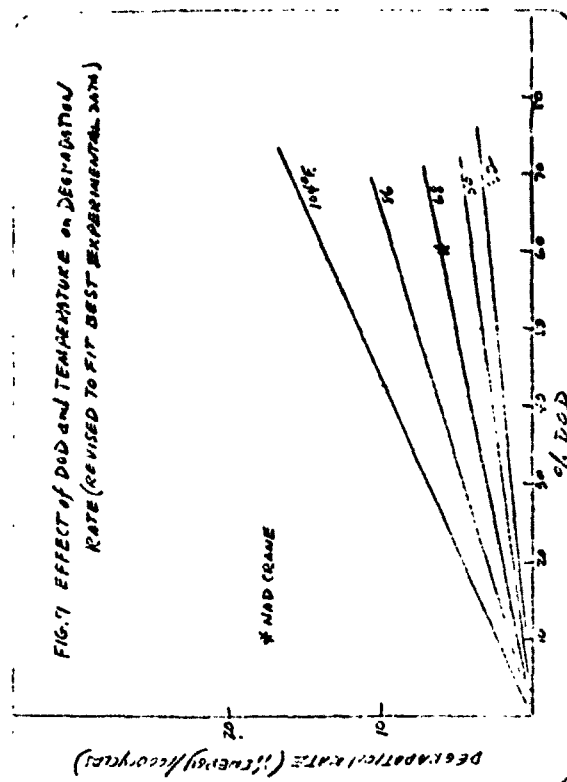


FIGURE 152

FIGURE 151 NOT AVAILABLE

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1h43

point in there is a real data point. The rest of them are just straight lines which we said derived on the basis of our assumptions and also the correction of the values of the change of slope for temperature.

Now, that wraps up the model building, and that last set of life curves which we have showed you is the basis which we will use to predict life in the new Crane tests insofar as we can do it on the basis of changes in depth of discharge and temperature.

We did something else in making those predictions also. We said, well, we have had now two nice jumps in performance. We will say when we get another one it will be 10 percent better. Maybe it's going to turn out to be considerably more than that, but anyway, it makes us conservative and we can change our model as we go -- I mean change numbers on the model as we go.

I would like to discuss this a little bit, to discuss the model a little bit, and point out that inherently this model encompasses the discharge rate variable which was worked into our matrix up to values of 2C where the discharge time was pegged at 30 minutes, and also I think 1C for the charge.

We will say then that the model, as it stands, is an exact mathematical description of cycle life behavior based on the assumptions, and the assumptions have been put into accord with test experience to the extent now possible. And, of course, it's heavily weighted on the basis of test experience in the ranges of 25 to 60 percent DOD and 68 to 104°F.

Now, the model itself does not deal with failure mechanisms, although we are tacitly assuming that failure is arrived at through degradation of the acid material and the plates' capability to produce capacity. And really that's the kind of a failure mode we would most rather have, because if that's the way they fail, then we are getting the ultimate out of our battery for any particular condition.

If they explode, if they leak, or if they do other things, then we are not pushing, we are not getting all that the battery itself, the active material anyway, the electrochemical part of that system is capable of producing.

We might also say that premature failures by internal shortcircuiting or case or terminal leakage in the vacuum environment, or exposing them to pressure buildup, might even be predictable if the things that are producing degradation of the capacity also result in these other things occurring.

Now, as it stands, the model predicts infinite life for 0 percent depth of discharge at any temperature, and it

1h44

predicts zero life at 100 percent depth of discharge. Now let us look at this first one of these statements.

We know very well that the N.Cd cell has a finite rate of self discharge and it is quite low at temperatures around 50° but it gets pretty high if you go up toward 100 or over. Zero percent depth of discharge corresponds, consequently, to the condition of constant trickle charge at the proper rate to just balance out discharge with any particular temperature. And the information which we have been getting yesterday from TRW and Hughes is the kind of information that we need, again to look at these low depth of discharge conditions.

Now, regarding 100 percent depth of discharge, the model cannot be exact either, because we have seen cases where capacity has improved a little very early in cycle life. But this improvement effect is so short-lived that this limiting condition is really almost correct.

And finally, if the percent depth of discharge is calculated, as is usual, on the basis of a nominal capacity rather than the actual initial capacity, then the definition of 100 percent depth of discharge would have to be correspondingly adjusted.

One more curve, please.

(Slide 153.)

We can take -- oh, that's the final wrap-up of cycle life versus depth of discharge.

Next curve, please.

(Slide 154.)

This is an Arrhenius part of the degradation rate data, and if you use it and calculate the activation energy for the degradation mechanism, it turns out to be 6-plus kilocalories. This kind of a value we are commencing to see a lot in battery chemistry. For instance, I reported on accelerated life testing of primary batteries, and the failure, the degradation rate, for these was, I think, 7,000 cycles. So I don't know what this means exactly. I just brought it up as a point of interest.

Now I would like to run my own critique and my own model. Then you guys can tear it apart as you see -- as you please.

There is one other tacit assumption that has been made in building this model, and it is this, that the rate of capacity degradation -- well, it's not "tacit," I guess, it's more than tacit.

The rate of capacity degradation is linear with numbers of cycles. Well, on the basis of that RAE data, we can't really say that but we will use it anyway in order to give a simple way to construct a model and look at it in terms of available information.

I don't care whether that curve turns out to be linear or not, because actually I think it's more like an "S" shape.

(Slide 154a.)

But as cycle life progresses, the capacity degrades on a curve like that. Whether it's a simple matter to get a representative equation for this kind of a curve, if we knew this was really true, and use that instead of linear relationship which we have already used to give us a refinement on our model, this would be then more realistic in terms of what's actually happening.

We have to know what the shape of that curve is first, and we don't yet, I don't believe. I think it's this, but I'm not sure. Well, anyway, using the linear relationship, how serious is it?

I don't think we would even care about whether it's linear or not if it were to become even approximately true at high numbers of cycles, because that's where we want to really be. We want to be in a condition where we can get high numbers of cycles in service.

And if it's actually as shaped, as shown here, then the shape of the curve at large numbers of cycles would be controlling for low depths of discharge and low temperatures, and it would be the shape of this curve if small cycle numbers would be controlling for large depths of discharge and high temperatures.

So we might even resolve the situation this way and make it a little bit simpler than using the equation for this curve but what we got is this. And the next step which I am going to do is to take these two intersecting straight lines and rebuild the model on that basis, if I can get enough information to tell me what's happening or approximate it anyway..

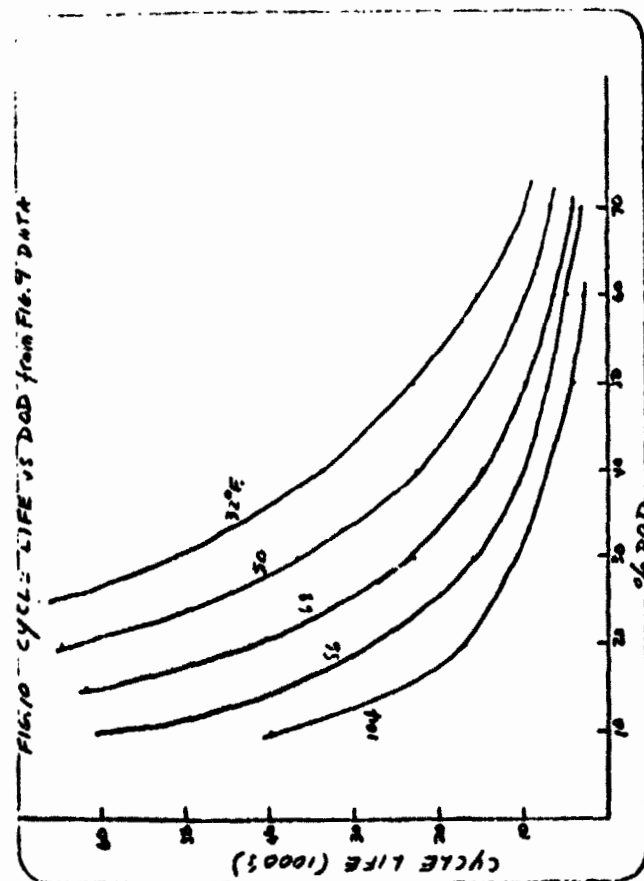


FIGURE 153

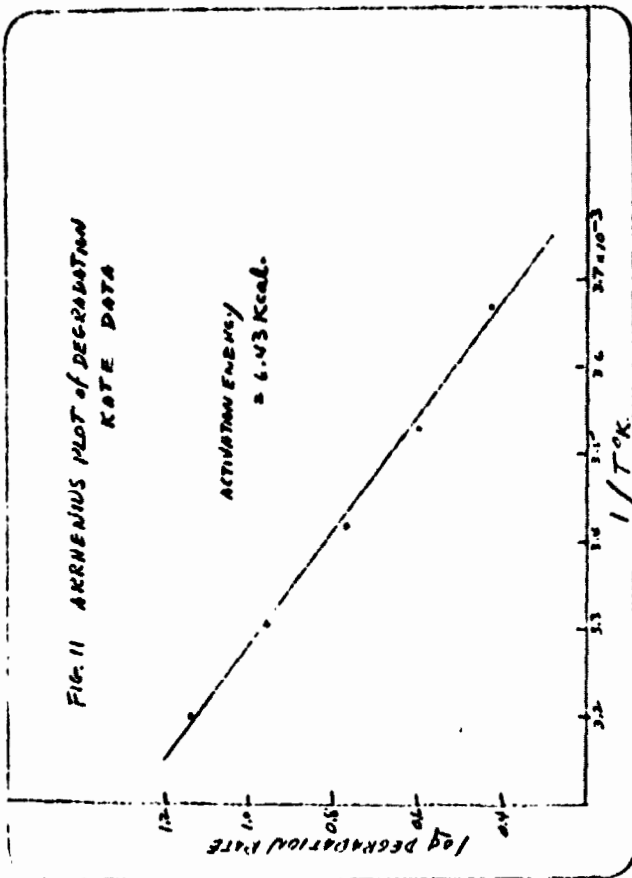


FIGURE 154

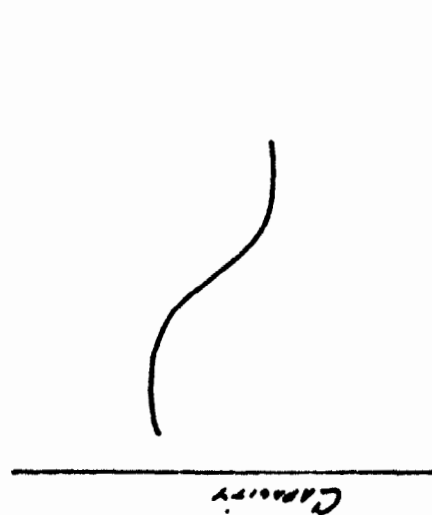


FIGURE 154A

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Now, talking about small depths of discharges and cycle numbers and low temperatures, the values of the degradation rate are highly uncertain. We just don't have enough information for those kinds of conditions to give us good, firm numbers. Or either the scatter in the information we have now is so bad that you might as well draw one great, big circle for a point down in that part of the graph.

Now, at the other end, that is, high depth of discharge and temperatures, we have little data again to describe the degradation rates as, except that we know their values

1h46

and we can't operate practically under those conditions anyway. So, as far as the model is concerned, it's nice to have it and maybe we would be able to use it to predict life and maybe we won't, depending on how good a resemblance the model actually is to reality.

Now, what we want to do really is to operate space cells at maximum depth of discharges which are consistent with the desired cycle life, and we would like to be able to operate them at as high a temperature as possible. And for lower orbiting vehicles, we are talking now that we would like to have life for five years and 25,000 cycles.

We can get this all right. This information, even the excellent information that we have says we can do it, but we don't really have the information yet which says, all right, how far can we push this battery toward maximum depth of discharge and elevated temperatures and still allow us to do it?

Okay. Now, how would we use this to predict cycle life for five years and 25,000 cycles and get us, let's say, a reliable accelerated test? Well, you go toward the higher depths of discharges and the higher temperatures to accelerate and if this kind of a model is representative of what's really happening, or if we can refine the model to something that is more nearly representative of what's actually happening, then we have a tool for prediction, because we have the mathematical relationship.

Okay. That's about as much as I have to say, and the floor is open.

DUNLOP: One comment. You talk about capacity degradation. Are you talking about capacity to a certain voltage?

LANDER: Yes.

DUNLOP: What voltage?

LANDER: This particular set of graphs was based on 1.0 volts. The Crane test data is going to be run down to 0 volts, I think.

DUNLOP: The degradation on the basis of capacity at 0 volts I don't think you will see it.

LANDER: See what?

DUNLOP: I don't think you will see a degradation. You won't see it. At least all the test data we received and

1h47

the test data I received from Hughes and other companies on certain batteries made by certain manufacturers, show an actual increase in capacity with cycling, not a decrease. I am not debating there is a failure mechanism or degradation mechanism that comes into play. I don't think it's capacity of the positive electrode that is -- that you observed as increasing it.

LANDER: I'll answer that by saying yes, there is a situation in which you can get zero degradation from zero volts, or approach it anyway, and the situation is for a high rate of discharge -- well, whatever it turns out to be.

I have some aircraft batteries, for example, that are approaching -- well, right now they may be 30 percent of their original capacity. We can still get all the capacity out if you are willing to go to a low rate and accept zero as the limit of voltage.

DUNLOP: The point I am making is simply that there are obviously degradation mechanisms. However you equate them in your equations, you are going to get to some point where there are certain factors that relate to degradation. I guess what I am saying is I don't believe capacity is the criteria that you should use as your degradation.

LANDER: Okay, what would you like to use?

DUNLOP: That's what you should be finding out in your tests.

(Laughter.)

LANDER: Let me tell you why I use capacity, okay? If you measure capacity at a given rate, it certainly does degrade. And that report of RAE's, for example, shows it very thoroughly. And it does degrade along some sort of a curve like this, and I think I know what these breaks mean. I think this is bound up with the inefficiency of the positive plate, charge inefficiency.

In this, now, after you get rid of that particular controlling condition, you run into another one which then becomes negative plate, very slow degradation of capacity in the negative plate.

SULKES: Sulkes, USAECOM. It's a rather interesting curve. Do you think there could be any relationship, let's say, between certain stand conditions and the low depth of discharge? That is, we could say a year standard at a certain temperature is in effect equivalent to so many cycles at 5 percent depth where you can take care of these stand conditions, using the same equation?

1h-48

LANDER: Actually I have done it, but, as I said, the low rates, the low depths of discharge in all temperatures, the data is extremely uncertain. And I think that the kind of data that was given by TRW, Hughes, and Comsat yesterday gives us more information about that situation than anything else we have yet.

LACKNER: This question isn't necessarily directed to Dr. Lander. Perhaps the manufacturer. We heard the comment "standard battery," and we have a life prediction model, and several of the manufacturers did say that you could design a vacuum for low temperature operation that may not work at high, for high depth or low depth, and vice versa.

Perhaps for standardization of cells we should try to standardize not only capacitors, the physical size, but on a performance level that you want for your high temperature cell or low temperature cell, a high depth of discharge.

Then these prediction models perhaps could be a lot more accurate, because we wouldn't get the randomness of the different designs into it. And if there are any of the manufacturers that care to comment on how we could come up with standard designs according to function rather than capacity, I would be very happy to hear it.

LANDER: I think that is a good point. I will let the manufacturers answer in a moment. I have one thing to say first. This may be all right where you can control your temperature and environment, but in aircraft batteries, for example, we have to cover an awful range of temperatures. And we have some very high rate performance situations to meet. Any other comments, say, from the manufacturers, on it.

FORD: Ford, NASA/Goddard. I am not a manufacturer.

(Laughter.)

Two comments, one with regard to Dunlop's comment about the capacity at zero volts. While in synchronous orbit, we do have a very real increase in capacity. We don't necessarily see that -- the capacity at zero volts does definitely degrade. It's a function of depth of discharge.

I guess in the last two or three years in the Crane test program we confined capacity to one volt, but they are also testing a number of packs now from a half a volt to zero volts with a capacity test. We are seeing what the dynamic of the capacity between one volt and zero volt is.

The second point with regard to your curve, I would like to talk to you after the meeting sometime, because I have

1h-49

some data that pretty well indicates the "S" shape function that you have indicated for three depths of discharge.

LANDER: Great. I would like to use it.

STEINHAUER: You indicate that your degradation may be a positive determinant at lower depths, and a negative determinant at higher depths.

LANDER: No, that's not depth. This is cycle number.

STEINHAUER: Okay. Do you believe that the negative plate -- can you extrapolate that negative plate at a lower part of that slope back? Do you believe that that plate has been degrading at that rate all the time or that it is an interactive thing with the positive?

LANDER: I really can't answer that. I think it is an interacting situation, and thus early, very early loss in capacity is quite marked at high temperatures and high depths of discharge. You see it right now at 18, 20, 50 cycles.

HALPERT: They are speechless. On all of these discussions figures were used. Of course, we would like to have them for the text and for the proceedings which will come out after the meeting. So for those of you who have not left us with figures, we would appreciate it if you would. And for drawings and so on, they would have to be drawn separately. They will be included.

Also I might add if you were here today and you weren't here yesterday, we would like to have your name and address for our record. There are some pages up front here for you to sign in with.

Our next speaker is going now to put some of these predictions to life and talk about life cycling of nickel-cadmium cells. Bill Harsch of Eagle Picher.

HARSCH: For the last two and a half years at our facility we have been conducting an accelerated life test on some nickel-cadmium cells. The test was funded jointly by Eagle Picher in-house funding and Lockheed Missile and Space Company.

The intent of the test was several-fold in the beginning, however as it ended up we only had one group of cells go into the actual testing due to some equipment failures and some wrong decisions on ceramic seals.

What we have is one pack of eight cells which have four different separators, two nonwoven nylon of 10 mil and 8 mil, and two nonwoven polypropylene of 10 and 8 mil. The intent was to keep as many things the same as we could, so

1h50

consequently we varied the thickness of the cell to accommodate the heavier separator so that we could maintain as close to the same cell compression as we could. The electrolyte levels are basically the same on all the cells.

The cells are cycled at 13 percent depth of discharge. These are rated 45 ampere-hour cells. The temperature again on the chart it shows 40 degrees. It is not. The cell packs are stabilized at 54 degrees, and they vary approximately two or three degrees during the cycle.

What we did to accelerate the test was not to accelerate any of the variables except for the cycle time. Our intent was to see how many cycles we could get from the cells under conditions that the cells would normally see. And it was geared toward a flight program so there was no intent to make it a classic type test.

It is constant current charge with a voltage clamp on the power supply so that as we approach end of charge we have a slight current drop. It's a constant resistance discharge.

Would you put the first slide on, please?

(Slide 156.)

What I plotted here was the end of charge and end of discharge voltages. These cell numbers here, the top two cells are two cells that have the 10 mil nonwoven polypropylene. The middle two cells are the 10 mil nonwoven nylon. The next two cells are the 8 mil polypropylene, and the bottom two cells are the 8 mil nonwoven nylon.

And, as you can see, for the first, at least first 5,000 cycles, there was very little difference in any of the cells. They looked quite identical. From that point on, we began to see some voltage degradation in the polypropylene cells up here, and on out to 10,000 cycles.

At 10,000 cycles we considered taking the first cell out. It was approaching 1.1 volts. However, we left it in the program.

Put the next slide on.

(Slide 157.)

Now, as we continue from there, at 13,000 cycles the cells were looking pretty bad, especially all of the polypropylene cells, with a rather wide voltage diversion, so we ran a capacity check on them at this time. Incidentally, all the cells now were approximately 47, 49 ampere hours.

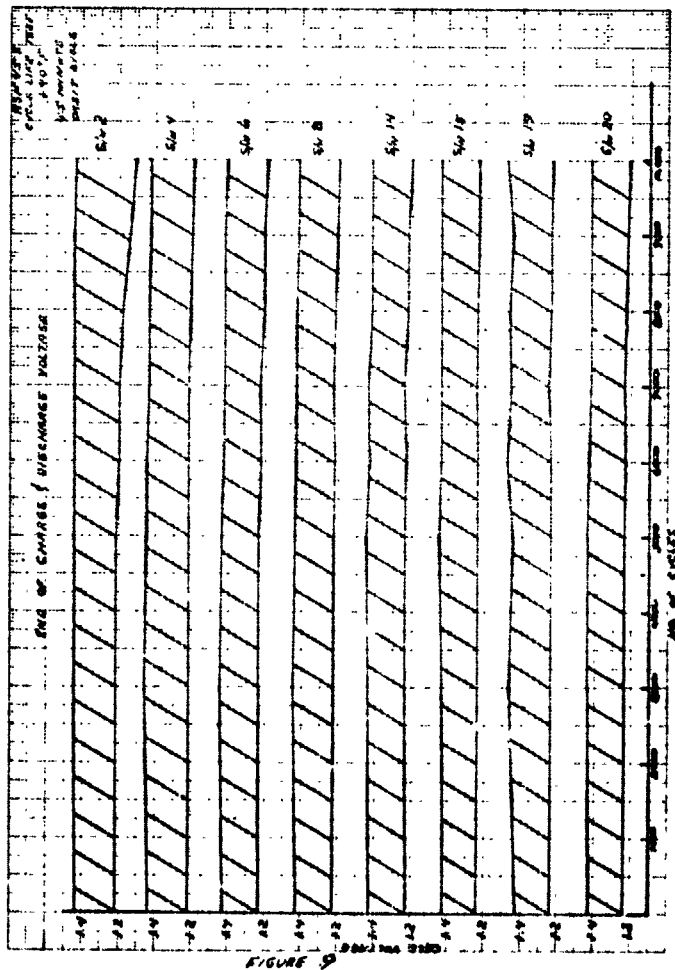


FIGURE 156

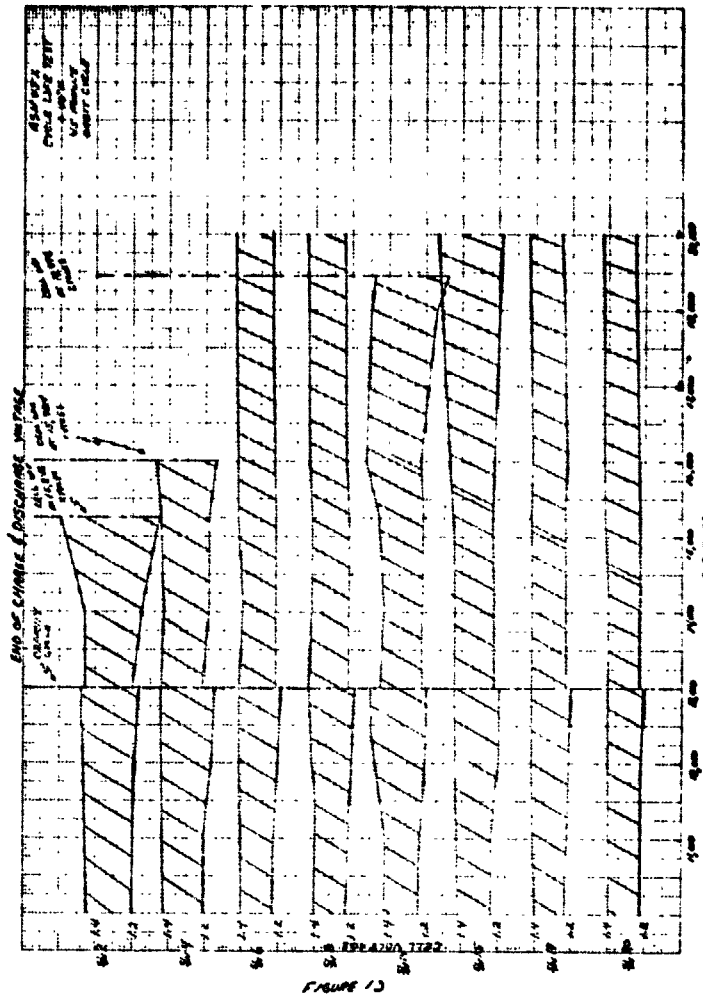


FIGURE 157

FIGURE 158 NOT AVAILABLE

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The capacity check at 13,000 cycles, the nylon cells, particularly these two, gave about 47 ampere hours. The other two nylon cells were about 45, 46 ampere hours. Both polypropylene, all four of the polypropylene cells were in between 25 and 27 ampere hours.

After the discharge, we put a full charge on them and another discharge. All of the nylon cells recovered full capacity. This one group of polypropylene cells recovered fairly good back to about 44, 45 ampere hours. These two cells here wouldn't recover capacity -- well, they did, but only to about 30 ampere hours.

So we put them all back on cycle again and, as you see, the two cells here quite rapidly fell out. Again they went out at 15,000 to 16,000 cycles, and we continued the testing. I plotted up to 20,000 cycles. We are approaching 22,000 now, and this cell is still hooked into the string, but for all practical purposes other tests were seen, like 1.56 volts at the end of charge and almost one volt at the end of the discharge.

But really, that's all I had to say about the test other than there is one more thing that may be noteworthy, in that the thinner nylon cells actually look the best at 21,000 cycles. And if I remember right, last year or the year before I remember someone else finding this out during long cycling. These are the 8 mil rather than the 10 mil nylon.

HALPERT: Are there any questions or comments?

SCOTT: Were the nylon materials laundered -- treated in any way?

HARSCH: I am sorry I didn't mention that. Two and a half years ago we didn't know as much, I guess as we do today, and we did things that maybe we wouldn't do today. The nylon cells were the same nylon as we have been using in all aerospace cells. The polypropylene cells, which were the two materials that were most attractive to everybody were washed as it was in most tests, they were methanol washed.

LURIE: What was your regime?

HARSCH: It is a simulation of a 90-minute orbit cycle. We have cut the cycle time in half. It is a 45-minute orbit, approximately 23 minute charge, 22 minute discharge, and we have doubled the rates that we would normally use in a 90-minute orbit cycle, so the rates are about 15 amps, somewhere in that neighborhood, 13 to 15 amps.

LURIE: You put in how much more charge or discharge?

1h52

HARSCH: The ratio works out to be 102 percent, 101 to 102 percent, just enough to maintain it. In this type of a test, we are not trying to drive the cell like you would if you were just sitting in on the bench and running the test to see, you know, what the cell looks like. This is something we want to go for some period of time, and so we adjust the rates, we rock them in so that the voltage stays the same cycle to cycle. And this works out to be somewhere like, at this particular temperature which is quite efficient, 102 percent maybe, in that neighborhood.

LACKNER: If I remember the list charge correctly, it looked as if the thin nylon and the two cells for the thin polypropylene were among the best.

HARSCH: No. Both of those were nylon at the end. Both polypropylenes are the ones with the wide diversions.

LACKNER: Could you put that slide on again?

HARSCH: Yes.

(Slide 157.)

These two cells here and these two cells are the polypropylene cells.

HALPERT: Okay. Any other comments, questions? Thank you.

Our next speaker has another approach to nickel-cadmium cell modeling. Gary Bizzell, Lockheed Corporation.

BIZZELL: Could I have the first slide, please?

(Slide 159.)

My presentation will describe highlights of work that we have done to model the NiCd cells. I would like to recognize people that have worked with me though on the project. In addition to myself, J. E. Shelton of our Palo Alto Research Laboratory has helped in the early phases of the modeling, and Mr. Sheldon Kay who has participated extensively in preparing the computer program that I will later describe.

The model building began about a year ago in mid-1972, with the objective of defining ways of modeling the charge control, thermal control interaction of the NiCd cell when used on spacecraft. However, our attention soon focused on the formulation of a mathematical model of the NiCd cell.

1h53

We moved in this direction, because something like this was needed, at least in my mind, to analyze a whole collection of test data that I couldn't understand because there were too many variables, and to guide the formulation of new detailed calorimetric tests.

Now I would like to make another point of recognition. Later I will show quite a bit of data taken with a calorimeter that was put together at Lockheed sometime back, and Marty Gandel has guided the collection of this test data. Going on to the next slide.

Our approach has been to marry together a certain amount of empiricism with what we hope to be a preponderance of basic electrochemistry. We examined the literature and compiled, according to our tastes, what appeared to be a plausible set of mechanisms. And I am sure I could get a long debate on this issue.

We tried to not be too finicky. You might describe our approach as taking a bag of pebbles of all different sizes and running a very coarse sieve through them, and we came out with a handful of mechanisms that we chose to attempt to represent.

The literature researched, we looked for papers where bench tests were done of physical chemistry type approaches and tried to then write rate expressions, conservation laws, as we knew them from the literature, and then assemble them altogether into an electrochemical system where we could then program the mathematical equations and then try to simulate the cell.

Of course, this is not done without some test data and, as one of our objectives, we would like to perform a minimum number of experiments to establish the model. Now, things are dynamic here, and as some of the data was collected we found that some things we hadn't bothered to think about needed to be considered and added into the model.

In addition, in formulating the computer program our approach was to be flexible. In other words, eventually put this thing in the open literature, and other people who knew a lot more about electrochemistry than I do could perhaps apply their own emphasis to mechanisms. The model is very capable of accepting alternate choices of mechanisms; numerics of this program though are extremely efficient.

For example, a 30-hour charge-discharge operation can run for about 30 seconds very nicely. As a matter of fact, we find that our work goes most efficiently by setting at a remote terminal to our 1108 computer and actually

1h54

charging the cell and discharging it in that position by just simply having an 1108 interact with us.

In identifying the physical-chemical steps that we wanted to represent, the first thing that we had to do was say something about the positive electrode. We chose two valence states, nickel 2, nickel 3, we didn't try to add any other species. And we adopted the idea that the action takes place on the positive electrode largely and that the negative electrode is largely passive.

Secondly, we took the position that at high states of charge the cell potential is strongly dominated by the inefficiency reaction, which is the production of oxygen. This is something that I satisfied myself in the program only a couple weeks ago -- and some of the slides I will show will not have this in the final form we have it now. The last series of slides that we will see has part B and I think an acceptable approach.

The third assumption is that the oxygen generation is controlled by the kinetics of the reaction on the surface of the positive electrode. Of course, it is a porous electrode, and therefore we have to propose some kind of thin, surface layer.

The fourth assumption, the oxygen recombination is controlled largely by mass transfer processes to the cadmium electrode, but rates differ depending on whether you are charging, discharging, or open circuit.

The fifth assumption, the self discharge is determined by chemical kinetics. It turns out this is something that is very minor and probably best representative of anything in the whole model but yet it's not something that one is interested in in looking at short term cycling of the cell.

Finally, and I should have said in energy balance here, a straightforward energy balance for the cell is an adequate energy balance for describing the heat effect, provided one has calculated the previous things correctly. In other words, if we get all of our individual rates correct, then we should be able to compute the heat effects, if we can write a good energy balance.

As a matter of fact, the first one I wrote a year ago was a good one, and I haven't changed it since, and the

1h55

handbook values that I put in there I have not meddled with. In addition to these basic steps, the program requires mechanisms for open circuit and transients when altering the sign or magnitude of the cell forcing current.

As we tried to put together the electrochemical system, however, we discovered that we had to include these turning points. When we changed the forcing function, we were exposing ourselves to something that we hadn't considered in this original list.

First of all, we would like to have a few representative charge-discharge curves for various temperatures and currents. Secondly, we would like to have some overcharge data for various temperatures to establish the oxygen combination-recombination, or generation-recombination rates.

Third, we would like to see plots of the cell pressure and cell heat rates for comparison with the simulation results: in other words, we are going to be calculating these two quantities, so why not measure them directly and compare your theory with experiment.

Finally, we would like to have the cell free volume. When you do a pressure calculation, you certainly will have to know the free volume. And then as much information as we can glean from the manufacturer of the cell as possible on how he made the thing, all benefits us in establishing areas, porosities, peripheral type information that is required as input to the computer program.

Sometimes we have a fairly good list of information from the manufacturer, sometimes it is pretty sparse, making us in a position of having to guess values. These data are, as I have listed them, are best obtained in a calorimeter where temperature control can be maintained and the heat effects directly measured. And we at Lockheed have a flow calorimeter which seems to do an acceptably good job for this, and I will show you some of the data later on.

Well, enough said about our approach. In the time I have remaining, I want to go through nine slides, which will be reproduced in the meeting proceedings showing the results of the work.

So let's have what I would call Figure 1.

(Slide 162.)

FIGURE 160 NOT AVAILABLE

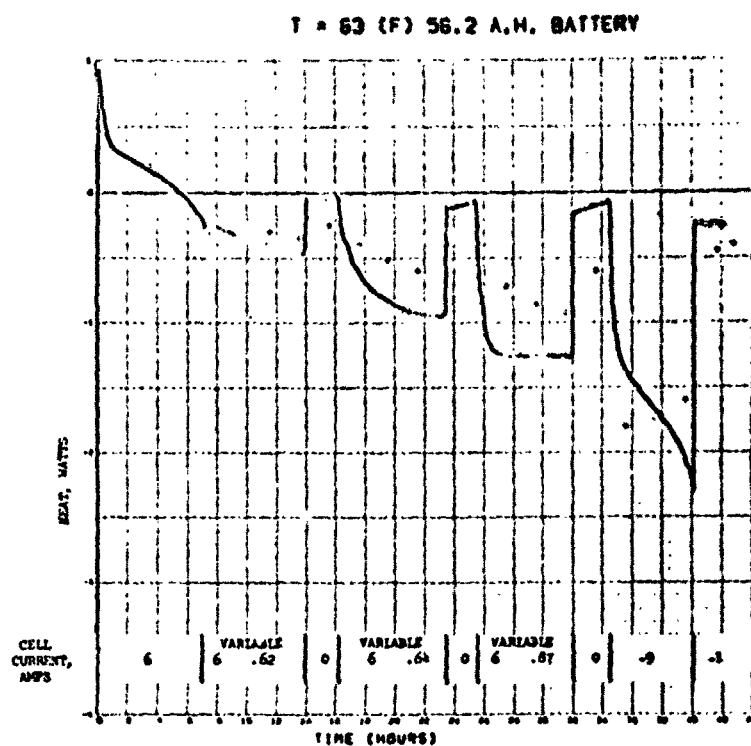


FIGURE 162

DEVELOPMENT OF NUCLEAR - GAMMA CELL MODEL

G. D. BIZZELL
J. E. CHILTON
S. RAY

SPACECRAFT THERMODYNAMICS DEPARTMENT
LOCKHEED MISSILES & SPACE CO., INC.
SUNNYVALE, CALIFORNIA

FIGURE 159

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FIGURE 161 NOT AVAILABLE

1h56

Figure 1 is some calorimetric test data that was obtained with an Eagle Picher nominal 45 amp-hour cell. After taking these data and operating the model, I would call this particular cell about a 56.2 amp-hour cell, because, of course, in a model of this type I am interested in the actual capacity and not a nameplate capacity.

Now, down at the bottom of this figure you see the current that was used for this series of continuous testing, going out to about 43 hours. We were plotting cell voltage. Some of the test data are shown on the figure just so that you could vary it in a curve if you had to.

The solid curve represents the computed curve from the mathematical model. You see a charge-up, you see a process of going into overcharge at a constant voltage of 1.45 volts, with a variable decreasing current. We go open circuit where we will have recombination. Then we go again at a constant voltage of 1.475, again with variable current. Then open circuit, then at 1.5 volts open circuit, finally a discharge at 9 volts, and at the end we further discharge at 1 volt.

The little tail on the end of the discharge curve there at 1 volt is something that came out automatically in the program as part of the mechanisms chosen, so I was quite gratified to see it appear there.

For this particular voltage curve, let us now look at the heat effects that we measured and calculated. This is at 63 degrees. The solid line again represents the computed value. The points represent the measured values. You can see that I am generally a little more exothermic than the calorimeter. Perhaps there are a few heat leaks or inefficiencies.

Now the legends for the charging and discharging currents are given across the bottom as before.

Let's go on now to the observed pressure.

(Slide 163.)

I am plotting pressure in atmospheres, and again, the solid curve represents the computed value. The points are the data. The little glitch at the front of the curve there is where my programmer decided he was going to condition the cell for me, and he let it overcharge quite a bit there in the earlier cycles. And of course the cell remembered, and since the pressure built up substantially it hadn't all recombined when I started my part of it, the simulation.

We can see that the pressure does recover and give a fairly good representation of the data. The thing to know

1h57

here is that the pressure is a maximum of about 1.5 atmospheres at 63 degrees, and when I show you the test data at 88 degrees you will see the pressure substantially higher, but the model does try to find that new level of pressure.

Let's go on to the case at 88 degrees for the same cell.

(Slide 164.)

Here we are plotting a different type of test. I like to say that we got smarter in the previous test. You notice that we are actually collecting some overcharge data while we are doing this. And I found that it was better from out standpoint to charge the cells and then go at constant current into overcharge as opposed to going at constant voltage. We seemed to save money that way, things were faster.

Again, we exercised the cell according to the prescribed currents across the bottom of the figure. You see, the problem that I mentioned earlier that I think I corrected very nicely, and that was as we got into overcharge I was very dissatisfied with the representation of the voltage curve.

And I think allowing the oxygen generation reaction to dominate the cell potential at that position fixes that up very nicely. This is at 88 degrees.

Now let's look at the heat effect at this temperature.

(Slide 165.)

You see the heat effect is substantially larger, and the energy balance, theoretical energy balance does seem to monitor the data reasonably well considering the complicated charging and discharging processes that we are using.

Let's go on to the next slide.

(Slide 166.)

Here is the corresponding pressure. You can see at this time we are up to around 70 psi in the cell, and the program does get to that level. Now this is one type of cell having a nameplate value of approximately 45 amp-hours. We have just recently, about three or four weeks ago, have computed some results for a larger cell having a value of around 60 amp-hours.

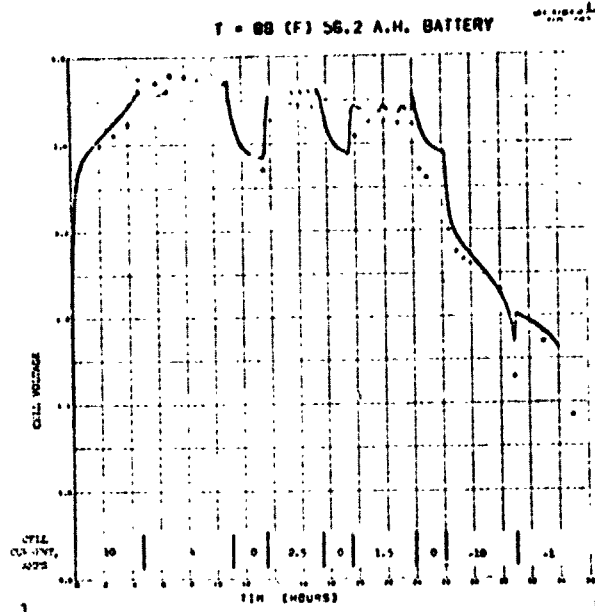


FIGURE 164

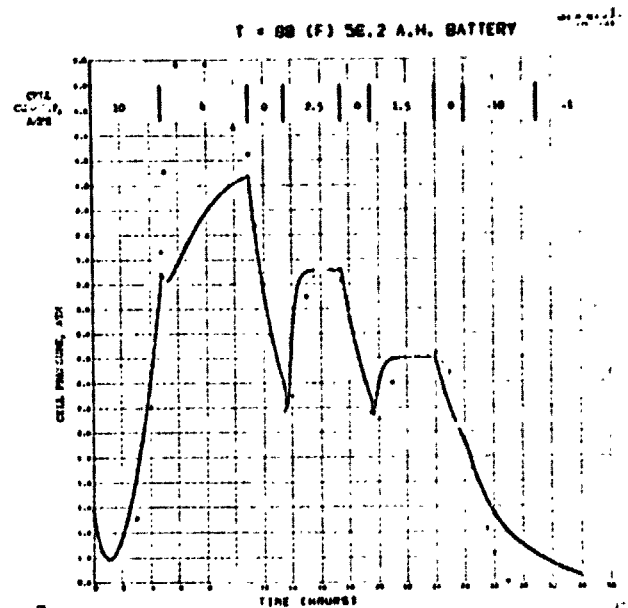


FIGURE 166

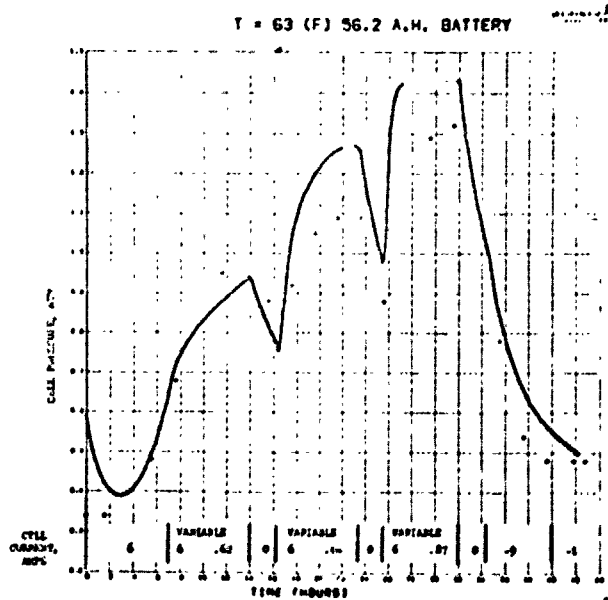


FIGURE 163

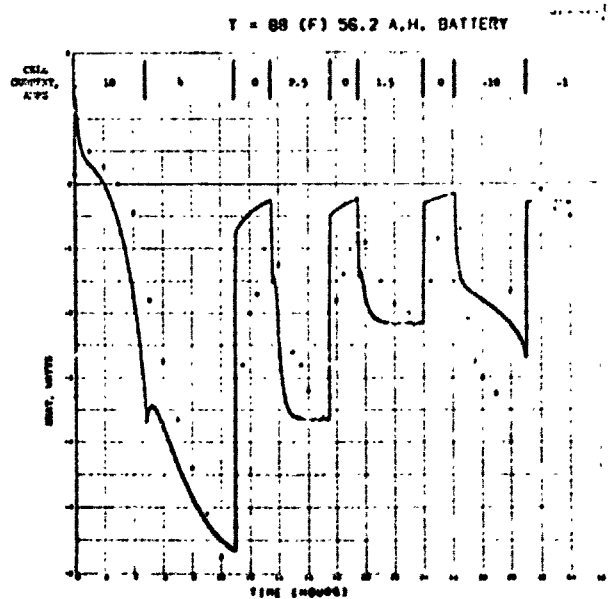


FIGURE 165

ORIGINAL PAGE IS
OF POOR QUALITY

1h58

So if we can have the next figure.

(Slide 167.)

This particular cell is, again, supplied by Eagle Picher, and I have had the occasion -- we have not been able to take very much data yet on this cell, but I wanted to show you the adequacy of the model. It was practically nothing to go on, and actually we used a lot of the values from the previous case, just scaled them up a little bit and computed these values. And this is the second run I made.

The first run I did have to adjust the voltage curve a little bit by a constant amount. This time I plotted the cell current that we exercised the thing with across the bottom of the figure. The 20 amp. discharge you see on the right should have one more square of the curve. It was mis-drawn there, so I will correct that now.

On this particular one, the thing that dissatisfies me the most is the open circuit voltage down at the end. I have to work on that, obviously. But I was reasonably gratified at the amplitude of the voltage for the 14 amp charge and the 7 amp charge, and the way the voltage curve nicely moves into the overcharge situation at the end of the 7 amp charge. Let me point that out for you.

This is the 7 amp. charging position, and here we are now decreasing the current as we go into overcharge, and you can see that the change in the rate of voltage is computed at that position. It does seem to give an excellent representation of the data.

This is the voltage curve comparison. Now let's look at the heat effect comparison.

(Slide 168.)

This is the measured heat out of the cell instantaneously with time. You notice we have approximately a hundred hours of continuous testing under control condition, very accurate temperature control. And the heat effect is shown as the solid line and the data represented as the circles.

Now we will go on to the next curve.

(Slide 169.)

I had a miserable time on this one with the pressure. I had so little data for the cell that my modeling of the pressure, I think, is fairly poor at the present time. The difficult thing is that the generation rate can get to be

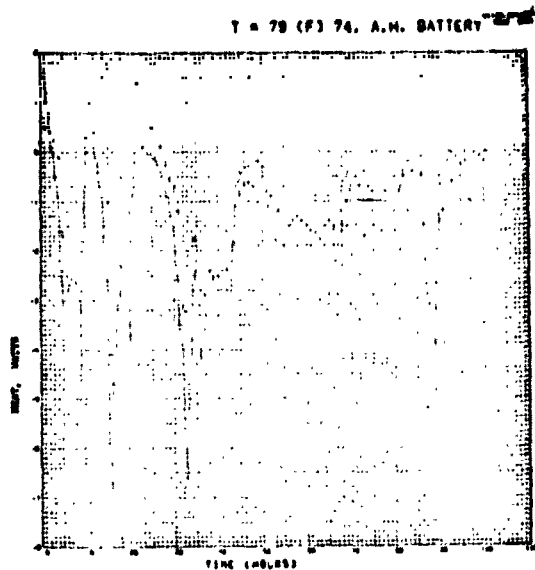


FIGURE 168

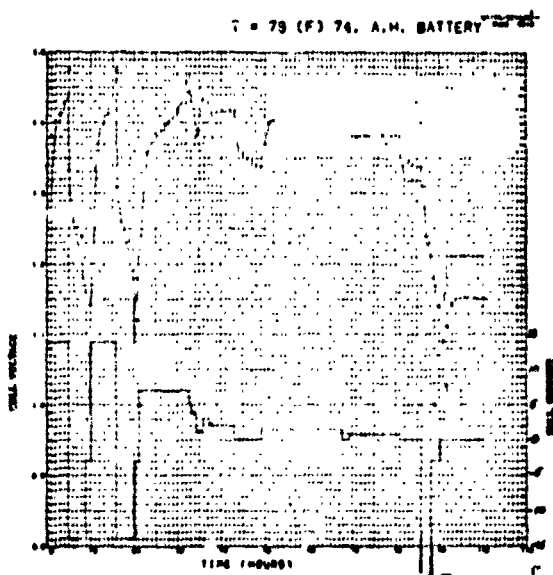


FIGURE 167

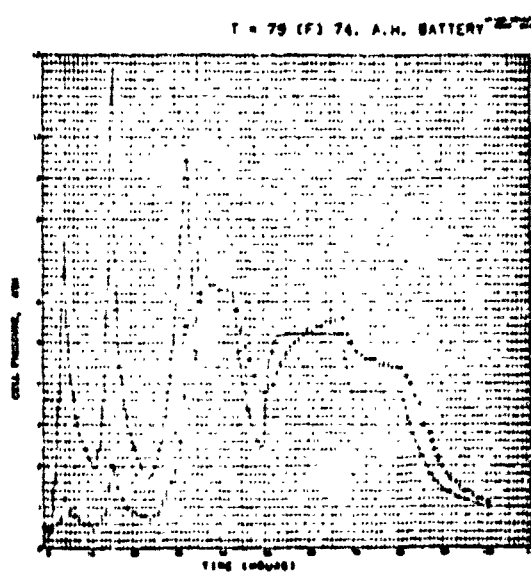


FIGURE 169

ORIGINAL PAGE IS
OF POOR QUALITY

1h59

extremely large, and the recombination rate can get to be extremely large, and I am taking the difference in curves and integrating it to represent the pressure of the cell. And you are really subject to inaccuracy and accumulation of error.

This is the last slide of my presentation.

HALPERT: Thank you.

Are there any comments or questions?

GINER: Jose Giner. What type of equation do you use to relate the voltage, for instance during charge, to the state of charge, time, current, and so on

BIZZELL: The representation of the voltage is done by a fairly simple equation. We are concerned with the state of the surface of the nickel electrode. We layer the electrode, and then compute the concentration of active species inside the electrode.

We update the activities of the component species on average throughout the cell. I didn't try to compute activities at OH^- and everywhere in the cell. The equation for the cell voltage has essentially one arbitrary constant. However, I have taken the liberty to turn that into two arbitrary constants by one for charge and one for discharge.

At the present time, I have a feeling that I may eventually settle on one constant because I would like to compare the model with charge-discharge curves for almost a decade of current. In other words, everything from $C/10$ all the way up to 2 or 3 C, and then I think I may be forced to stick with one constant as optimum.

GINTER: Do you take into consideration polarization?

BIZZELL: Yes. I do account for ionic resistance. The polarization effects are not distinguished outright. I may be a little empirical there, but I don't go into Helmholtz's double layers. I like to see the concentration very high of the electrolyte.

There may be effects due to nonconductors acting as capacitors inside the cell and then relaxing after you remove, go into open circuit. I don't know. Some of these questions are, as I said, others are more expert than I am, and they might like to try their hand at their favorite mechanism.

LANDER: Where did you get your "S" term from?

1h60

BIZZELL: I think I used the values in Falk and Saltine's book, and probably compared them with Bauer's book, and maybe a couple of papers. It is unfortunate that I forgot to bring my report with me today, because I picked up another one with the same cover. But I did use simply hand-book values as standard references.

LANDER: I would just like to point out that the Bauer "S" values are kind of uncertain, because we don't really know what the Bauer "S" charge in the positive plate is. Recently Don Maheskie from our laboratory published a paper, a temperature study, where he did some heat pipe studies, and he used insulated cells and found the value of temperature change in that work. He computed pretty good value for the change.

BIZZELL: We could probably take our data too, and, say, obtain a better fit by adjusting some of these values. But I was more concerned in the rates and allowed the hand-book values to remain fixed, at least for now.

HALPERT: Thank you.

Our last speaker of the morning is going to speak about the improved energy density cell, 20 watt hours per pound, nickel-cadmium battery. Our speaker is John Armentrout of the Philco-Ford Corporation.

ARMENTROUT: My basic presentation this morning relates to the development of a light weight nickel-cadmium battery capable of delivering 20 watt hours per pound. The particular battery that we are showing here is of similar design to the design that we plan to have for the 20 watt hour per pound battery. I think it's on there backwards.
(Slide 170.)

This battery was developed as part of a program for NASA/Goddard, the SMS battery under the technical cognizance of Floyd Ford and Dave Bear. And this battery probably is yielding, based on actual capacity, maybe 13 watt hours per pound.

Can we have that next slide?

(Slide 171.)

Some of the concepts that we used in developing this battery, we used the standard nickel-cadmium design technology. The cell was made to the NASA Hi-Rol cell specification. The major weight savings, or part of the weight savings, came in going to a thin wall cell container design, a standard wall being 25 to 30 mils, and we reduced about 50 percent of that.

1h61

The metal-ceramic seals were originally rated at about 160 amps, and we used a smaller 12-amp hour type seal which is capable of sustaining about 80 amps continuous duty. By means of ratioing and weights with the standard electrodes, we were able to reduce a little weight and yet maintain a 1.5 negative to positive ratio capacity, or electrode capacity ratio for the system.

The actual battery assembly that you saw a moment ago consists of an intercostal structural packaging design. It's a "T" rib, which we will show in the next slide. Or one more, I think it is. Let's go.

(Slide 172.)

The intercostal is a magnesium material, and it supports four battery cells which the intercostal serves as our heat sink during overcharge and when we are dissipating any kind of battery heat. We also have, not shown in this diagram here, a resistor for maintaining the battery temperature in the event that we get too cold. And so the intercostal serves both as a heat sink and as a means of heating the cell.

The structure itself just consists of two end plates with the through bolts on either side. Each separate intercostal mounts and is a separate. You could extend this to as many cells -- this happens to be a 20 cell design that we are looking at here.

(Slide 173.)

To give an idea of where our weight savings were, if we took a standard cell and said that that was 100 percent, our cell was coming in at about 68 percent of that weight and of that percentage. If you were to compare the weights of standard electrode separator and electrolyte weight, you can see that we saved a little weight in that part of it.

But most of our weight was picked up in the covering container and there were some miscellaneous materials that we were able to eliminate.

Why don't we go two more now?

(Slide 174.)

The intercostal, as far as the heat dissipation is concerned, we have, in the particular designs that we have in-house right now, a Delta temperature drop of about two and a half degrees C, and that is under our worst case heating, during discharge our worst case heating condition.

ADVANCED 20 WATT-HOUR PER POUND LIGHTWEIGHT BATTERY DESIGN

BATTERY CELL

- o STANDARD NICKEL-CADMIUM CELL DESIGN TECHNOLOGY FOR SYNCHRONOUS ORBIT SATELLITES
- o QUALITY ASSURANCE PROVISIONS IN ACCORDANCE WITH NASA HIGH RELIABILITY CELL SPECIFICATION
- o FLIGHT PROVEN THIN WALL CELL CONTAINER DESIGN
- o HIGH RELIABILITY METAL-CERAMIC SEALS FOR CELL TERMINALS
- o HIGH NEGATIVE TO POSITIVE ELECTRODE CAPACITY RATIO

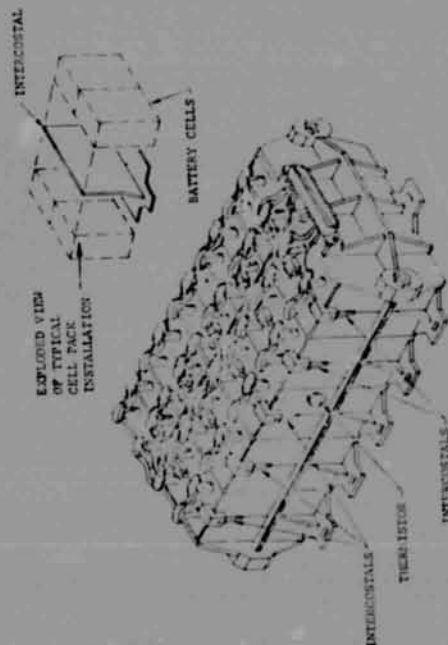
BATTERY ASSEMBLY

- o FLIGHT PROVEN INTERCOSTAL STRUCTURAL ACRAGING DESIGN
- o OPTIMIZED THERMAL DESIGN - MAGNESIUM STRUCTURAL MATERIAL
- o INTERNAL TEMPERATURE CONTROL BY HEATER ELEMENT THERMAL SHUNTING
- o FLIGHT QUALIFIED ASSEMBLY DESIGN



TYPICAL NICKEL-CADMIUM
BATTERY ASSEMBLY DESIGN
PHILCO-FORD MOD-30-020

FIGURE 170

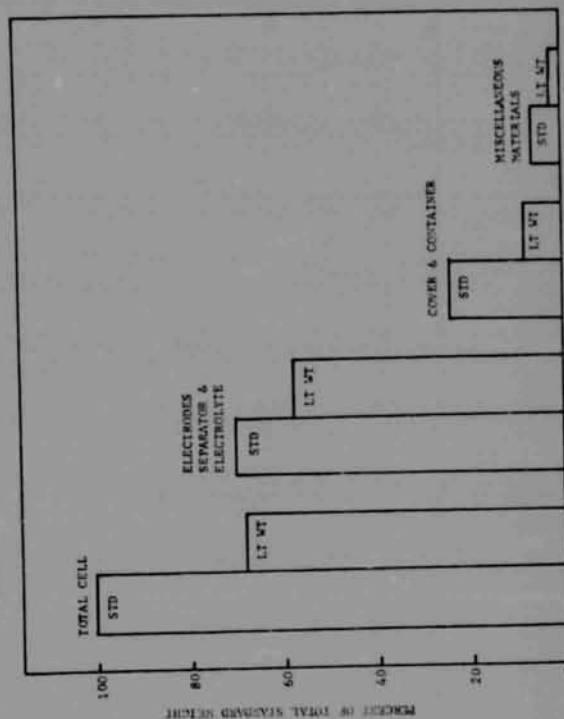


LIGHTWEIGHT BATTERY ASSEMBLY DESIGN

FIGURE 172

FIGURE 171

TYPICAL COMPONENT WEIGHT ALLOCATION - NICKEL-CADMIUM CELL

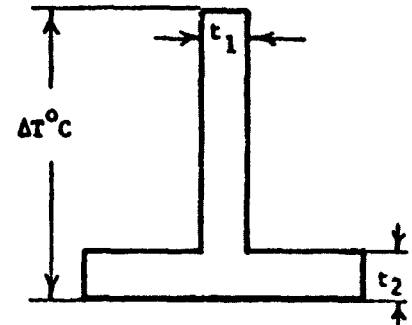


CELL COMPONENTS

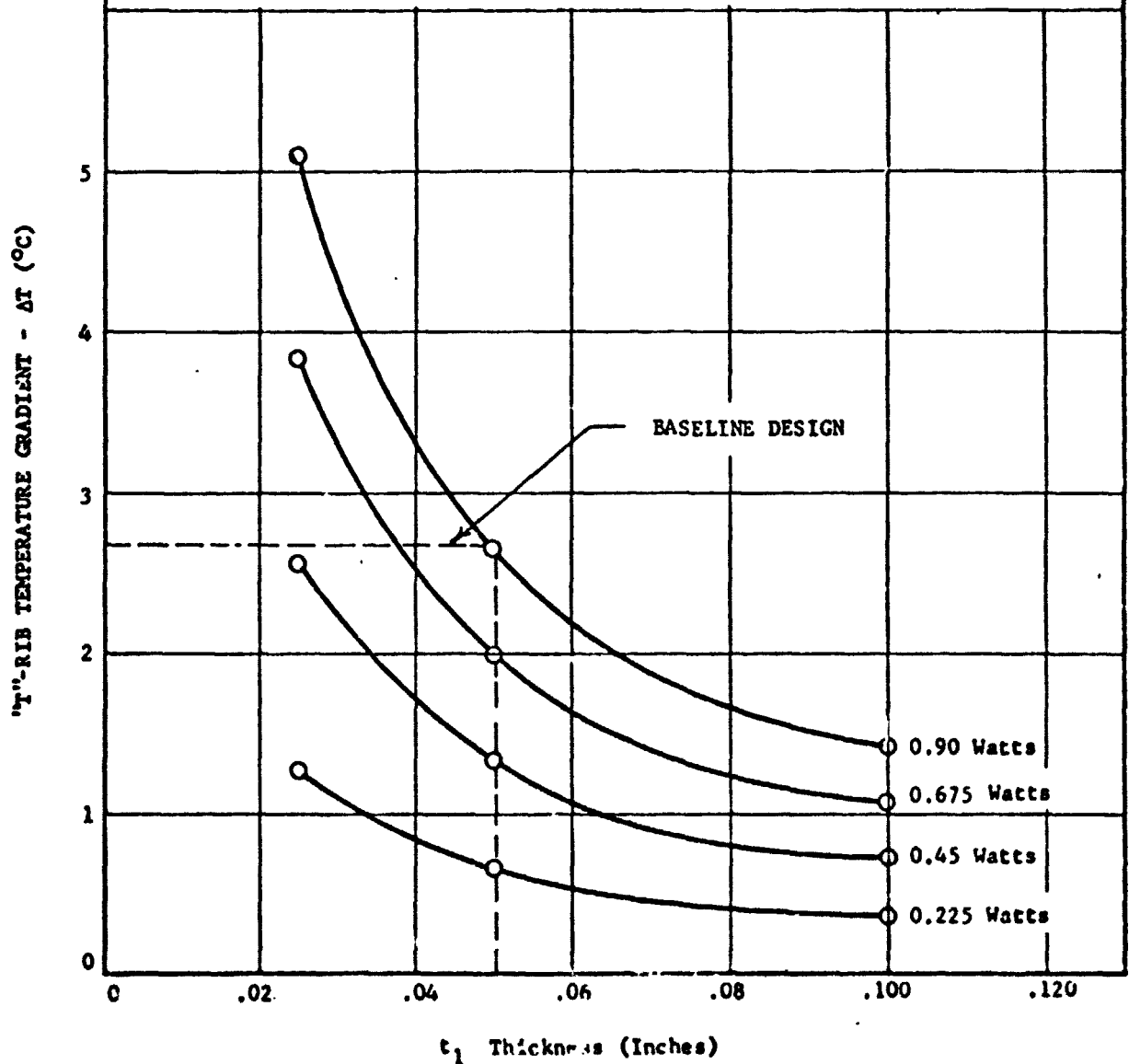
FIGURE 173

ASSUMPTIONS

1. $t_1 = t_2$
2. Base Plate Sink Temperature 70°F
3. Filled Base Joint
 $h = 250 \text{ BTU/Hr Ft}^2 \text{ }^{\circ}\text{F}$
4. 18 Watt Total Battery Thermal Load, 50% Dissipated to Base
5. Battery Cell Width 2.98"



"T" RIB SECTION



BATTERY ASSEMBLY "T"-RIB THERMAL ANALYSIS

1h62

This was used mainly in our analysis for determining what the dissipations were.

Can we go to the next? One more.

(Slide 175.)

Some of the actual numbers here, the actual cell capacity on the 20 watt hour per pound that we are talking about, in the temperature range of 30 to 80°F, is 25 ampere hours; with our negative to positive electrode capacity ratio of one and a half, our maximum cell overcharge pressure at a C/10 rate at 70°F is 65 psig.

And again, our maximum cell charging voltage C/20 rate at 30°F is 1.51 volts. The actual energy density of this cell, based upon the 25 amp. hour capacity, is 23 watt hours per pound. When this is packaged into our 20 cell battery, we are coming up with a weight of 27 pounds. It's actually a little under that.

The energy density then is calculated at about 22 watt hours per pound or a nominal 20 watt hour per pound battery. And, depending upon your depth of discharge, which we will show in a later slide here, the particular design that we have is a seven year battery operating in the 40 to 50°F range.

Could we have the next slide?

(Slide 176.)

To give an idea of where we are relative to typical designs that we have, you can see about the best that we have at the present time is probably, maybe 11 or 12 watt hours per pound, again depending upon your depth of discharge.

The current Philco-Ford designs that we have are approaching and going past 20 watt hours per pound, and we feel that in our optimized design we can increase that slightly, and possibly this curve might represent a little more closely our nickel-hydrogen, which Ron Haas will be talking on that and silver-hydrogen a little later.

There are two companies which are presently under subcontract with Philco for producing these cells: Eagle Picher and Heliotec. The data that we are showing here is actual data that we have gotten on some prequalification test cells. And the 20 watt per hour design that we are showing is in its early hardware stage right now.

The other design has been qualified, the SMS design, and we have been producing flight batteries with that design and had about six through acceptance tests, I believe.

DESIGN PARAMETER	VALUE
ACTUAL CELL CAPACITY TO 1.0 VOLT (30°F to 80°F)	25 AH
NEGATIVE TO POSITIVE CELL ELECTRODE CAPACITY RATIO	1.50
MAXIMUM CELL OVERCHARGE PRESSURE (C/10 @ 70°F)	65 PSIG
MAXIMUM CELL CHARGING VOLTAGE (C/20 @ 30°F)	1.51 VOLTS
ACTUAL CELL ENERGY DENSITY	23 WH/LB
20-CELL BATTERY WEIGHT (MAXIMUM)	27 LBS
20-CELL BATTERY ASSEMBLY ENERGY DENSITY: ACTUAL NOMINAL	22 WH/LB 20 WH/LB
SYNCHRONOUS ORBIT DESIGN LIFE (40°F to 50°F)	7 YEARS

[illegible]

NICKEL-CADMIUM BATTERY ENERGY DENSITY CHARACTERISTICS

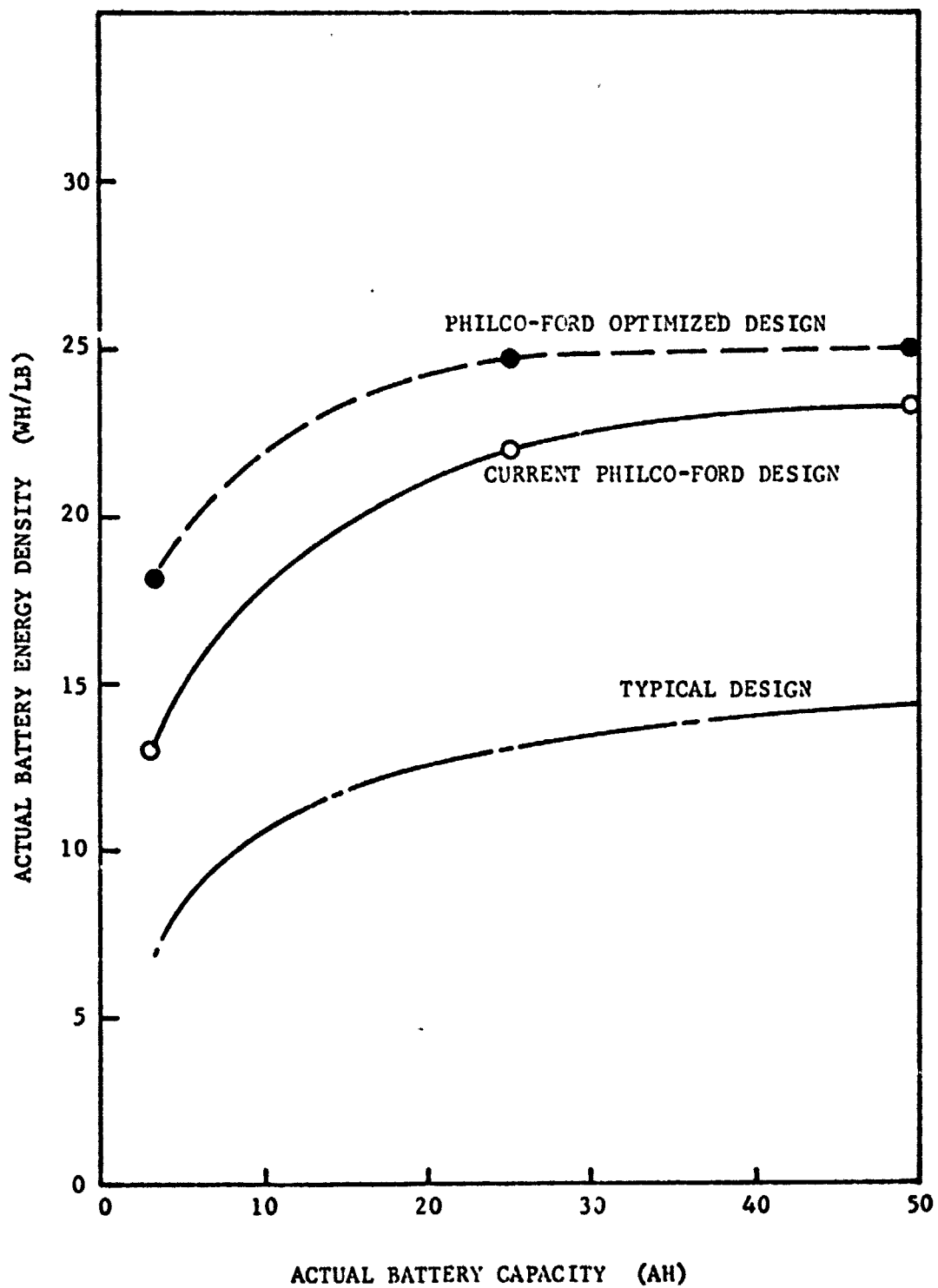


FIGURE 176

1h63

We have one more slide.

(Slide 177.)

This is taken from a technical report on the long-life battery of the Air Force. We are showing, with the subscript one, the original data that was plotted in that report. We have indicated preliminary designs as they were indicated in that report. And for our designs, which are flight qualified on the SMS Program, it is actually a five-year, 45 percent depth of discharge. If we were to drop that depth of discharge, we feel that we could go out to seven years.

The other system that we are working with is a seven-year, 24 percent DOD, and we feel that, were we to increase that, we could get five years and a little more watt hours per pound out of that system.

That is essentially all that we have to report. We are open for any questions.

DUNLOP: On the last slide the depth of discharge you were talking about is what? one degree?

ARMENTROUT: That's based on your actual capacity.

DUNLOP: The five year was what?

ARMENTROUT: Forty-eight percent.

DUNLOP: And the seven year was what?

ARMENTROUT: Twenty-four.

DUNLOP: I don't want to argue with you too much, but you notice that four is running at 60 percent. I may make some comments later, but that really represents usable energy density. The actual two last satellites we put up had a usable energy density higher than your --

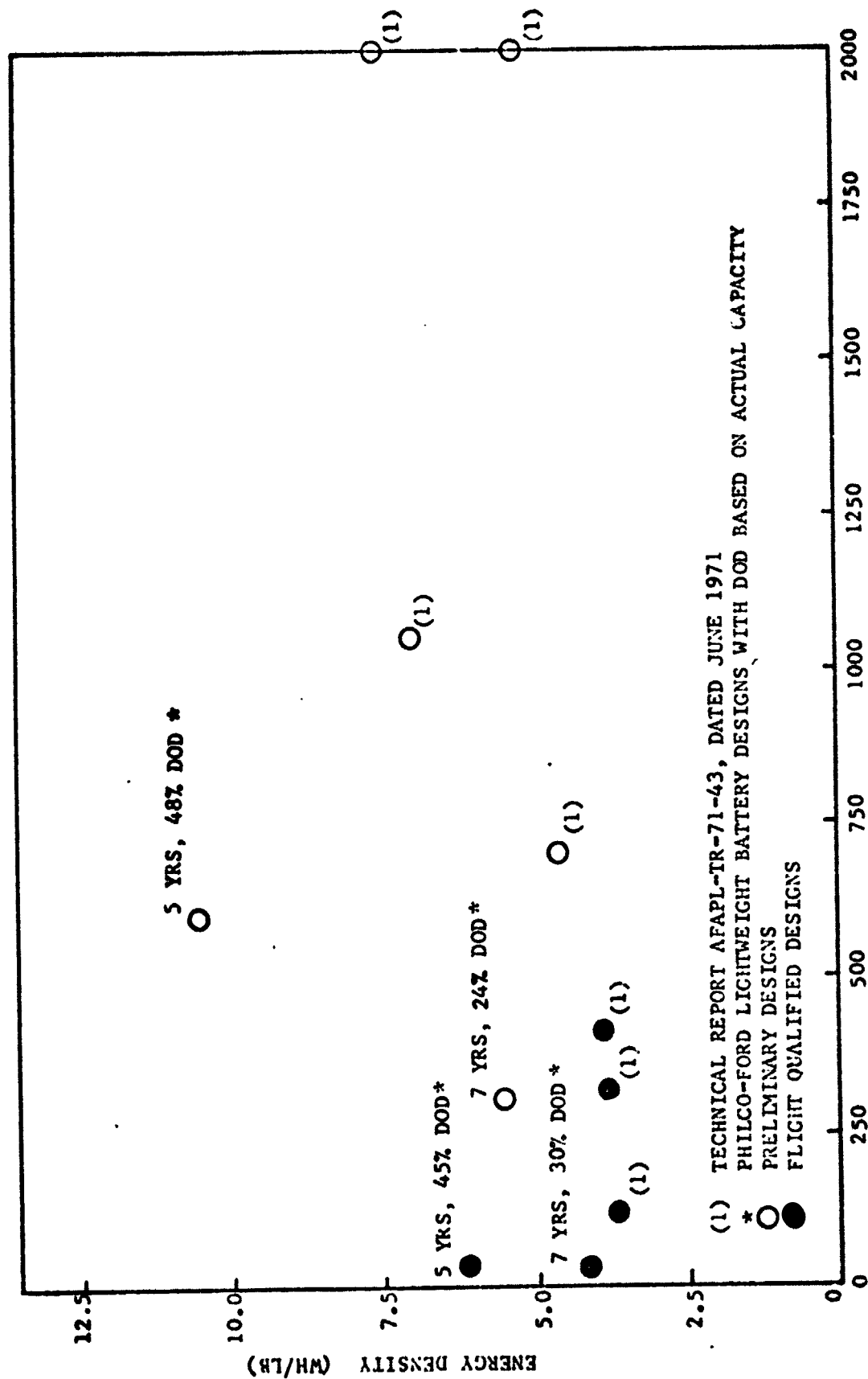
ARMENTROUT: Well, you get into reliability at that point.

DUNLOP: But I am not sure what your data recycling is.

ARMENTROUT: If you wanted to increase the depth of the depth of discharge, you are going to get a higher yield in watt hours per pound.

DUNLOP: The yields on solar systems are running pretty low. They are 60 percent of the rate but they are

BATTERY ENERGY DENSITY FOR VARIOUS SYSTEM LOADS



LOAD IN WATTS

FIGURE 177

1h64

still delivering around six to seven watt hours per pound usable energy.

ARMENTROUT: These are conservative numbers that we are showing.

DUNLOP: The question is why are they so conservative? Is it because of your lightweight design?

ARMENTROUT: It is our reliability that we are looking at.

DUNLOP: Did you sacrifice your energy density to go to your lightweight design? It almost seems that way.

ARMENTROUT: Ron, do you want to answer that? Did we sacrifice.

HAAS: Ron Haas from Philco-Ford. We have two basic customers: commercial satellite and military. The particular program that we are involved with on this 20 watt hours per pound average tends to favor DOD's. We are working on the Goddard program with a somewhat higher DOD. It is purely by direction from the customer.

SULLIVAN: I am not clear on how you calculate watt hours per pound. It's watt hours based on 28 percent depth of discharge or 100 percent depth of discharge?

ARMENTROUT: It's based on actual capacity that we show. For example, we are talking 5 amp hour -- or 25 amp battery ampere hours times, in this case, 24 volts for a 20-cell battery, and down to 1 volt which is your 25 amperes, and divide that by the weight of your battery.

SULLIVAN: You consider it down to 1 volt?

ARMENTROUT: When we make that calculation, yes.

STEINHAUER: You indicated a small temperature difference along the length of that thermal shunt. What is your worst case during charge, discharge, or overcharge from the center of that pack to the output of the cells?

ARMENTROUT: Ron, do you want to comment on that? I think that it's no worse than the drop that we indicated.

HAAS: The answer, Bob, is that it is a function of the platform construction. Typically they will put a thermal shunt, a slug, on it where we mount the battery with mounting screws. So it is probably in most cases a maximum difference of 7 degrees out.

1h65

STEINHAUSER: Are you actively cooling or is it passive cooling?

HAAS: We are actively heating and we are passively cooling.

HALPERT: Thank you very much, John.

At this point I think we can plan to break. I do want to tell you that we have not had all of our figures turned in for the speakers who have been presenting papers here in the last couple of days. It is important that we do get those in right away so we can get the proceedings published. The sooner we get them in, the sooner you get it back.

We will break now and return at 2 o'clock. I would like to thank Tom and Floyd for inviting me back to actively participate today.

en tp 1

(Whereupon, at 12:55 p.m., the proceedings were recessed to reconvene at 2:00 p.m. this same day.)

11-14-73
lh66
tp 2(1)

AFTERNOON SESSION

(2:00 p.m.)

FORD: Okay, if we can have your attention we will get started with the first speaker. Actually, the first speaker this afternoon is the last speaker for the morning's topic that we discussed, and after we get that one by, we will go right into the nickel hydrogen work.

I know that there a lot of you who have indicated to me you are going to have to leave early, so we are going to try to cover as much material as we possibly can. Again, I reiterate if you need any help with reservations or any way we can help you, please don't hesitate to call.

Now, one point I might make for the benefit of those who will be leaving. You do not have to go back through the main gate to get out of here. If you are going to Washington or Baltimore, the most direct route is to the right.

The road that runs by the front of the building, just go out and you have an exit either north on the Baltimore-Washington Parkway or an exit going south to Washington, and from there you can go to the beltway and get wherever you want to go. So it will bypass the traffic going through the main gate, also on Glendale Road.

Okay, at this time I would like to introduce Jon Rubenzer from Ames Research. Is he here? Okay, Jon, and his subject is "Magnetic Testing of Nickel-Cadmium Cells."

RUBENZER: I'll make this as quick as I can to get us on schedule as best we can. I work in the Advance Space Projects Office at Ames, and our primary concern with nickel-cadmium batteries is for applications in spacecraft designed for interplanetary missions of long duration, by that I mean in excess of around two years.

About a year and a half ago, Eagle Picher furnished us two Mumetal encased, 8 ampere hour nickel-cadmium cells, which we performed magnetic tests on to determine how the remanence field of these cells was hopefully decreased by the Mumetal encasing material.

Our interest in doing this specifically related to the fact that on most interplanetary spacecraft a magnetometer is carried to measure relatively low magnetic fields, both in the interplanetary portion of the mission, and sometimes at the planet, depending on which planet it happens to be.

Anyway, we performed our remanence tests on these cells. The remanence signature of the Mumetal encased cells as compared to stainless steel cells was so low that we thought it worthwhile to buy some extra cells and figure

1h67

in what I guess would best be called a "battery configuration," and see what they looked configured in that manner.

Our intent wasn't to identify or map the remanence field of any particular battery. It was more hopefully to establish some sort of base that various people that specialized in magnetics could use as sort of a rule of thumb or base estimates on what their battery might be if they happened to design it on nickel-cadmium cells.

The first slide, please.

(Slide 178.)

The first viewgraph just generally shows the cell axis coordinates that we assigned to the cells and adhered to throughout our magnetics testing.

(Slide 179.)

The second slide shows two configurations which will be referred to or referenced in the upcoming viewgraph which is self explanatory.

The next one, please.

(Slide 180.)

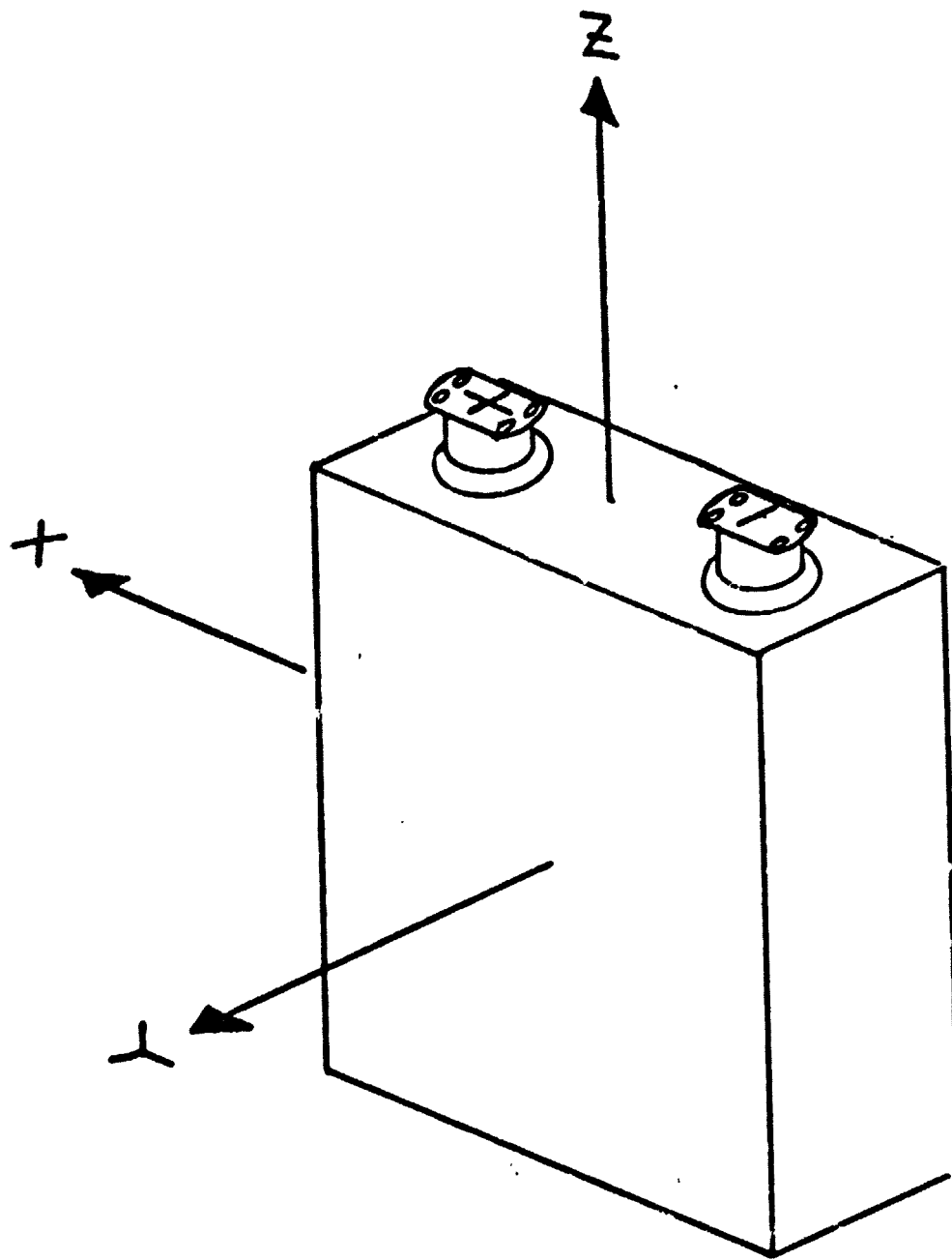
There is the last two. Again, this is self explanatory, so we will move right on.

(Slide 181.)

All right, when we got our 8 ampere hour nickel-cadmium cells encase in Mumetal from Eagle Picher, they were built and designed with what Eagle Picher calls, I guess, a "sponge negative electrode." Physically, they are the same size as the conventional 6 ampere hour nickel-cadmium cells.

They were sealed, ceramic sealed. Both the outer case and I guess what would best be called the cover were made of Mumetal. The first thing we did in our test, when we got our 28 or so Mumetal cells, was run a comparison with some of the other tests and look at the cells on an individual basis.

Quickly, the first cell shown on the chart is RSN6 with stainless steel case and cover and sintered nickel plates. This is the cell I just referred to in trying to describe the size of the 8's that we got. Because of the sponge negative feature, the 8 ampere hour units which followed, referred to up here, are identified as RSN8's, are the same physical size as the 6



CELL AXES CO-ORDINATES
FOR MAGNETIC TESTS.
(TYPICAL FOR ALL MODELS)

FIGURE 178

1h68

The post 25 gauss exposure remanence shown by this cell and the XYMZ axis as shown is self explanatory. In the interest of time, I will just very briefly identify the next three or four cells.

The following cell was an RSN8S, but it had a stainless steel case and cover on it. Following that was an 8S with a stainless steel cover also, a sample of two tested and there are the results of those.

The fourth column is an average of six of these metal encased RSN8S cells. These are the type that we bought 28 of and used throughout this testing which I am now going to describe. I very shortly will.

The last cell shown there was made by Energy Research Corporation. The details on it can best be described by Mr. Kline, because his organization made it. They came out and furnished us this cell because what was furnished at this workshop a year ago interested them, and they thought maybe they had an idea for something along this line also.

One last word on that particular cell: it was encased in plastic. It was not intended to be a sealed cell with a metal case and ready to go on a space application, spacecraft sort of thing. However, the primary purpose was to take a look at the internals of the cell.

They made an attempt, and succeeded apparently, in removing all the metallic nickel or any magnetic material from the cell, because after 25 gauss exposure, which is a pretty nasty field, it showed absolutely no remanence. It is just as clean as a silver-zinc or a silver-cad cell. If you want any more details on that cell, I am sure Martin will be happy to provide them. He knows a lot more about it than I do.

Next slide, please.

(Slide 182.)

Incidentally, we only had one of those cells so that is the beginning and the end of the testing we did on those.

Okay, this next chart briefly shows the results of the remanence of an RSN8S cell, six cells, after post 25 gauss exposure and after a post deperm, to give you an idea of how much they perm up and how much they clean up after we deperm the cells.

Next chart, please.

(Slide 183.)

Now we will get into some of the stack configurations that we tested. When we stack the cells together in

C-2

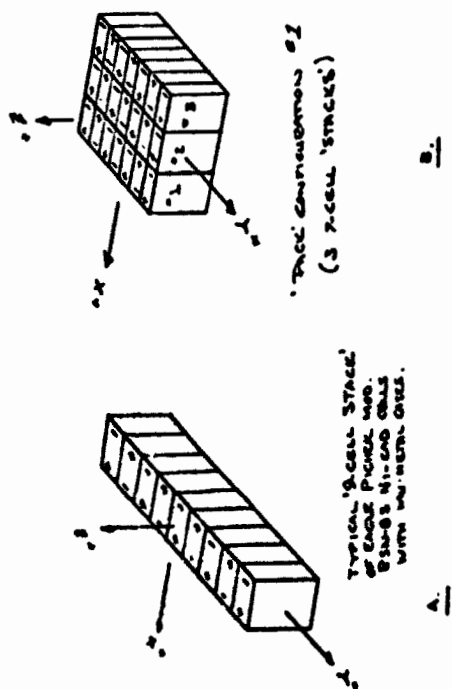


FIG. 2

FIGURE 179

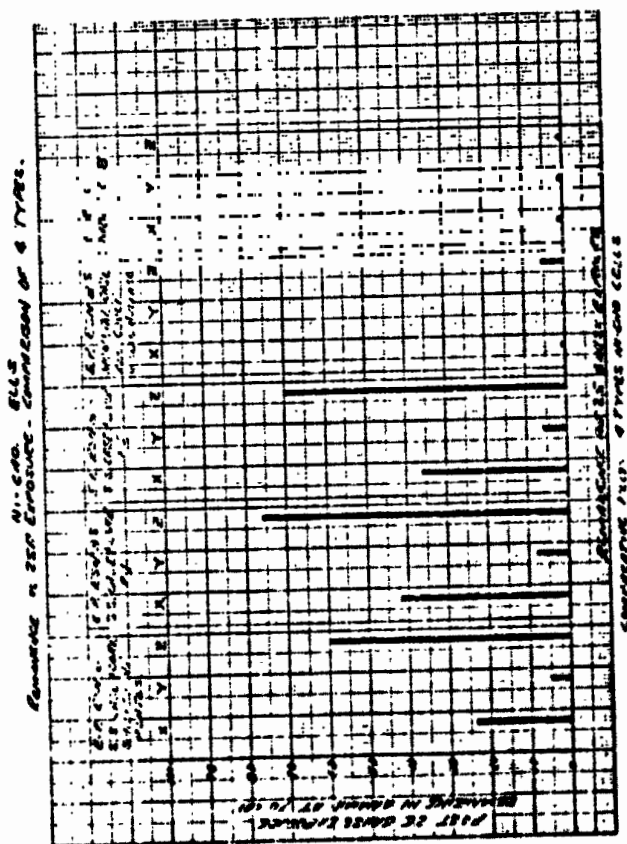


FIGURE 181

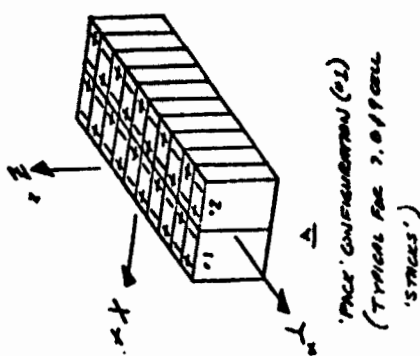


FIG. 3

FIGURE 180

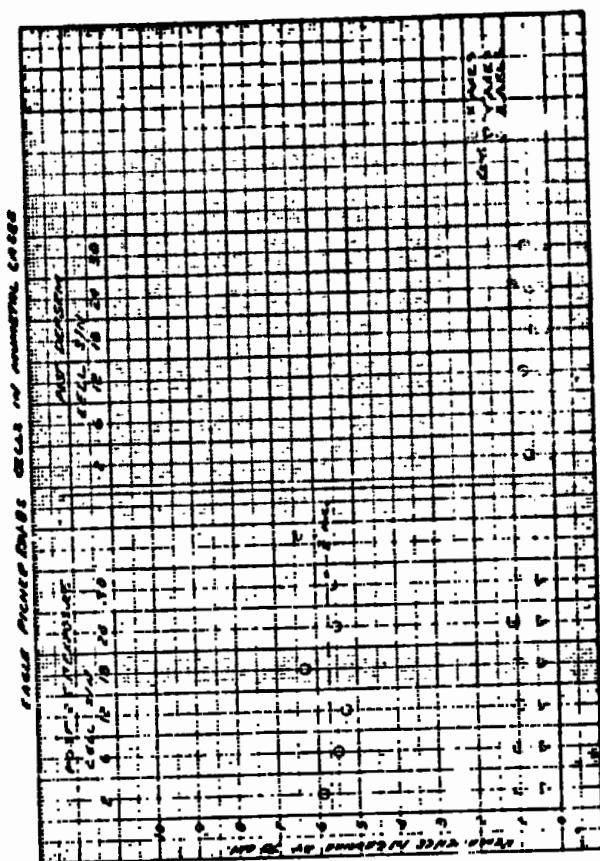
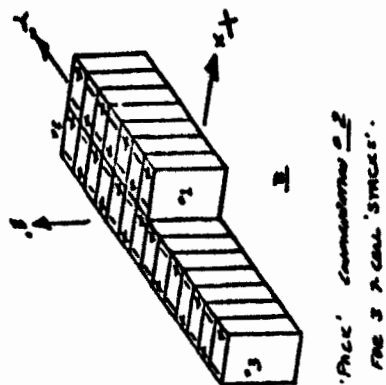


FIGURE 182

1h69

the order shown on the second and third viewgraph, we insulated them electrically because the negative electrodes were connected to the case in this particular application. This was done because Mumetal contains somewhere between 4 and 5 percent copper, and it was hoped that this would make things behave a little bit.

We have not tested these cells magnetically since we received them. They are right now in storage in open circuit discharge mode and will remain that way until one of these days a final contract, hopefully at least, will be selected for the Pioneer Venus Program.

And, at that time, if it is deemed wise or necessary one of these individual contractors, or even we in-house, might take an additional look at maybe some performance and see how they fared over the last year or so that they have been in existence.

Again, this is pretty self-explanatory. The first column -- I will just hit a couple of them -- is a 10-cell stack identified as stack number 1, followed by a 10-cell stack number 2. Again, we had 28 cells. The first stack, as I recall, consists of cell serial number 1 through 10 and the next were 10 through 20 or something along this line.

All the cells look pretty repeatable in their remanence signature so we found out after a while we really don't worry that much about keeping track of the individual cells. We were really looking for average numbers anyway.

Following the 10-cell stacks are three nines and then two sevens and two fives. We actually tested, I think, a couple more stacks than this, but the results were quite similar so only some of them are plotted up. I should say the results were repeatable, like I think three or four 7-cell stacks were tested.

As you can see, the shorter the stack got, the lesser the amount of magnetic material contained in it and the lower the remnants. Specifically, this particular graph gives a good idea of just how the remnant field increase as the stack length increases. That particular feature turns out to be the most significant contributor to the magnetic effect of the battery.

Next chart, please.

(Slide 184.)

This shows five additional cell configurations or pack configurations. The first column is the first portion showing the X axes of these different configurations, followed by the Y axes measurement, and finally the Z axes.

1h70

The first pack here is two 7-cell stacks, configuration one, and when all these things are included in the final report if you don't recall, the configuration one was two stacks right side by side, followed by two 9-cell stacks similarly arranged, two 10-cells, three 7-cells. Again, these three 7-cell stacks were three side by side. And then finally three 9-cell stacks.

This is kind of nice in that it-you can see just how the different geometry increased the

Next graph, please.

(Slide 185.)

Okay. This perhaps is a little easier for you to digest at this time without having all these stack configuration references and this sort of thing. From this it can be readily seen that the overall remanence of any of these configurations, or specifically of the two 3-stack configurations, is by far the first stack.

In magnetics or in these tests the magnetic field was measured on axes at 70 centimeters away from the geometric center of the cell stacks. If you take that magnetic component and rotate 90 degrees off the axis in any direction your field at that point is one half of what you measured on axis.

So, spacecraft being what they are, not always being allowed to position the battery where one would ideally, or the magnetometer experimenter would ideally like to put it, right on axis, the farthest point in the spacecraft away from his instrument, he inevitably ends up having to put the darn thing up on a top shelf or a bottom shelf or somewhere off axis.

And with this information he can readily calculate at any point in space what the remanence magnetic effect would be because of this battery, these battery configurations. Because of this, you can't just go out and look at the lowest number, like take the second configuration.

The X axes, we have something like 21 gammas for measured remnants. Well, that's readily identifiable as the lowest remnants on any of the axes of the first two configurations tested. But if you take the Y axis of that same stack and cut it in half and add to that, you find out that you are worse off than you are if you use the first stack, which is a little bit higher in X but not nearly as high in Y, because all these magnetometers flown these days anyway are three axes magnetometers. They don't just look at the X, they look at the Y and Z also.

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TABLE PICTURE PAGES MICRO CELL STACKS. MICRO CELL STACKS

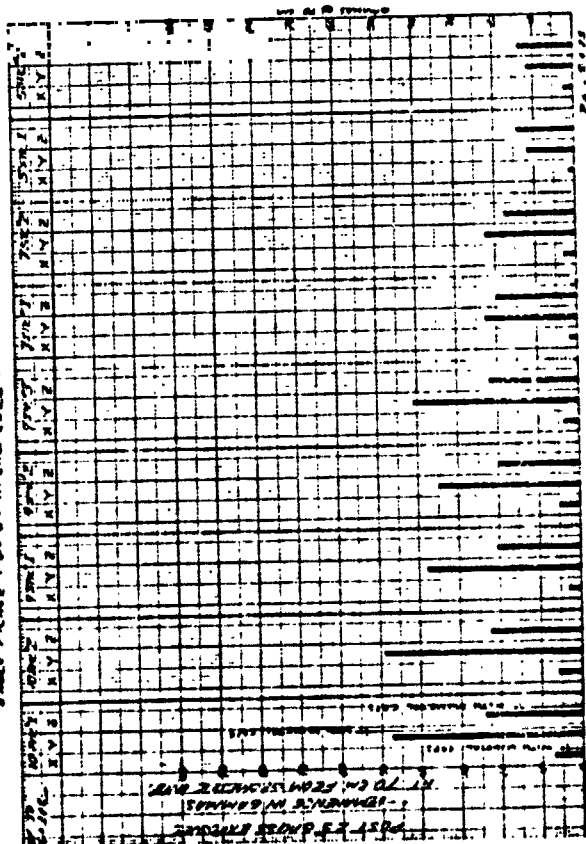


FIGURE 183

TABLE PICTURE PAGES MICRO CELL STACKS. MICRO CELL STACKS

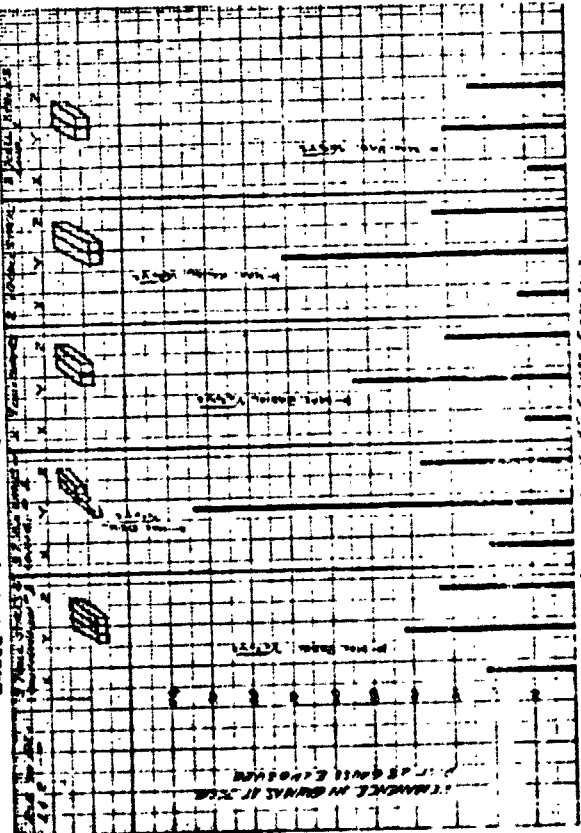


FIGURE 185

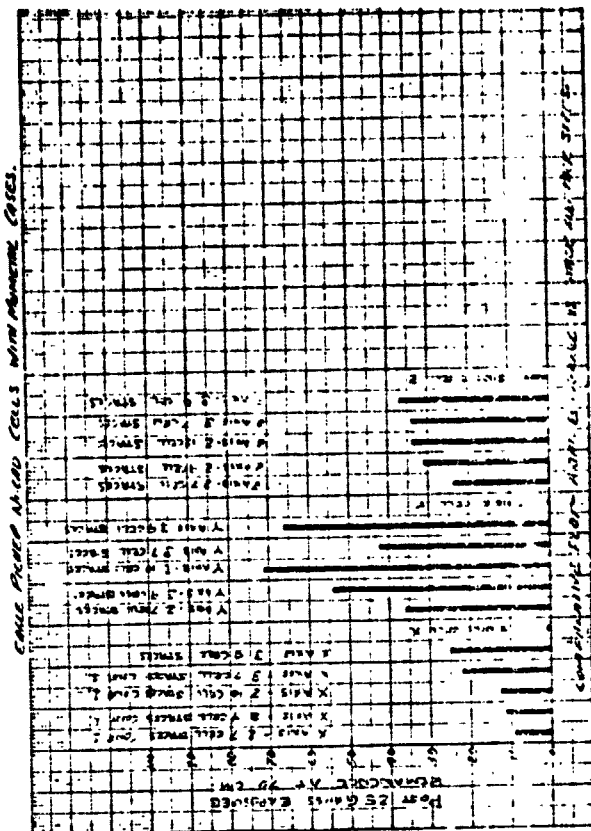


FIGURE 184

THE TEST DATA INDICATE THAT FIELD PREDICTIONS BASED UPON SIMPLE SUMMING OF THE REMANENCE VALUES OF A SINGLE CELL IS VERY INVALID. FOR EXAMPLE, THE Y AXIS OF A SINGLE CELL DISPLAYED ONLY 0.4 GAMMA AT 70 CM AFTER A 25 GAUSS PULSE, BUT THE Y AXIS REMANENCE OF FIVE CELLS STACKED SIDE-BY-SIDE WAS ALMOST 12 GAMMAS AND WITH TEN CELLS THE REMANENCE WAS ALMOST 50 GAMMAS. CONVERSELY, THE POST 25 GAUSS EXPOSURE REMANENCE IN THE X AXIS OF A SINGLE CELL WAS 1.0 GAMMA, BUT ONLY INCREASED TO 2.0 GAMMAS FOR A STACK OF FIVE CELLS AND TO 6.0 GAMMAS FOR A STACK OF TEN CELLS. THEREFORE, IF FIELD PREDICTIONS WERE MADE BY SIMPLY SUMMING THE SINGLE CELL VALUES, THE Y AXIS PREDICTION WOULD BE GROSSLY UNDERESTIMATED AND THE X AXIS WOULD BE OVERESTIMATED.

THE LARGE INCREASE IN THE Y AXIS OF THE CELLS STACKS SUGGESTS THAT THE NUMBER OF CELLS IN EACH STACK SHOULD BE SUCH THAT WHEN TWO OR MORE STACKS ARE ARRANGED INTO A BATTERY PACK, THE LENGTH-TO-WIDTH RATIO WILL BE NEARLY ONE-TO-ONE. THIS IS ILLUSTRATED BY COMPARISON OF THE POST 25 GAUSS EXPOSURE REMANENCE OF A PACK CONSISTING OF TWO 10 CELL STACKS TO THAT OF A PACK CONSISTING OF

THREE 7 CELL STACKS:

Axis	X	Y	Z
Two 10 Cell Stacks	22.5	71	34
Three 7 Cell Stacks	22	42	34

FIGURE 186

1h71

Okay, and the last chart.

(Slide 186.)

All this says briefly is that you can't take the remanence signature of a single cell and by adding scale up to a battery configuration. I don't think anybody expected that you could, but we wanted to find out if we could develop some information which would allow one to make at least an educated guess at how to scale up or to develop some sort of empirical relationship to achieve the same result.

And the last paragraph here indicates that, in most cases at least, it looks like one is best to design a battery so that -- of course, you have to tailor it to your own individual application for you should pretty much make it uniform geometrically in length to width at least, or somewhere near the same.

And that's all I have. Are there any questions?

FORD: Any questions?

Okay, that wraps up the morning session this afternoon. At this time I would like to have Jim Dunlop to come up to take over the session on the metal gas systems.

DUNLOP: I have to find out who the speakers are. The session this afternoon is on the hydrogen cells, and before we start this session I want to make one brief comment.

Yesterday somebody asked me a question I thought about last night. He asked me the question would we get seven years' life in an INTELSAT 4 satellite, and I said no. It's probably the correct answer if you consider the type of data that we have for the type of storage mode that we have been using, which is the open circuit charge mode with a slow rate discharge.

We actually are strongly considering the options of changing that mode, based on the data you saw yesterday to a triple charge mode. I want to make one more comment to put this in proper perspective.

The batteries that are used in INTELSAT 4 were built and delivered in 1969, and I think that -- usually I think most of our presentations sound like we are shooting down the battery manufacturers. I would like to say at this point in time that I think that battery choice was an excellent choice in 1969, and I would like to credit the battery manufacturer at that time with probably building a very good cell.

One of the things he certainly did was provide a very excellent negative-positive ratio on that particular

1h72

cell, and it's better than 2 to 1, frankly. And actually, electrochemically measured it is better than 1.7 or 1.8 to 1. And we have observed on this trickle charge mode that we are maintaining good utilization of the cadmium electrode even though it's in a cell.

And there was a lot of data presented yesterday showing that with that trickle charge mode we have successfully tested those cells for years with no failures in that particular mode, and the data looks very repeatable.

Now, enough for that. Nickel-hydrogen -- and the first speaker, it is my pleasure to introduce my colleague today, Jo Stoekel, who is going to present some of the work that we have been doing at Comsat.

STOEKEL: Thank you, James.

Gentlemen, this afternoon I would like to present a summary of the work that has been going on at Comsat Laboratories. And presently we are finishing a contract with Energy Research Corporation for the delivery of light weight nickel-hydrogen cells, the 50 ampere variety.

Our first slide here will be a summary of just what indeed is going to be delivered.

(Slide 187.)

We are essentially having four groups of cells, and each group will contain four cells. The first group here, the positive electrode will be a SAFT electrode with a platinum negative electrode and the separator here will be nylon.

Going across the top here, the other will be Gould, which of course you recognize as being the sinter, and one from Energy Research which is the pressed variety, and again over here we will have a sinter electrode made by SAFT. All the negative electrodes are the same. They are all platinum with the Teflon backing on them.

And the separators for this first group of cells will be nylon, nylon 2505, I believe, and the rest of the cells here will have the potassium titanate. This particular group here is a stack that is being assembled in our laboratory, and it will be delivered to ERC for assembly into their lightweight can.

And here, in my little show-and-tell sack, I have a 50 ampere hour stack that was built in our laboratory. This particular stack has double 40 mil thick SAFT electrodes. Now I say double. That means they are back to back. And it has nylon as a separator. It has a Teflon gas diffusion screen, and it uses a hydrogen electrode made by Energy Research.

1h73

This stack, as I hold it here, weighs about 602 grams. The pressure vessel here is a electroform nickel can, again from ERC. This can weighs, as I hold it in my hand, about 255 grams. The stack will be assembled in here. It will be held in place by a dome on the bottom that this will be mounted to, and the busbar in this case is a comb arrangement that will go down here and this will be the feed-through, and we are using the Ziegler-type seal for the feed-through.

This busbar weighs about 30 or 40 grams. So that pretty much -- if you load the electrolyte into the stack I estimate maybe 100 to 150 grams. That cell right there, as you see it including the pressure vessel, will give about 24 to 26 watt hours per pound as it sits on the table. That's to one volt.

We do now have a contract with, a new contract, with Energy Research and Eagle Picher. It was a split contract for delivery of 32 lightweight nickel-hydrogen cells. Those cells coming under this contract will be so-called "prototype design," and they will have to withstand dynamic loads.

Hopefully we will have those cells in-house for testing about eight months from now. In obtaining some little advance information on the differences between the nylon and the potassium titanate, a test was initiated using single electrode cells.

The next slide, Floyd.

(Slide 188.)

Shows particular cells that were used. They are just small, one and a half ampere hour cells. They used a General Electric back to back 27 mil positive electrode, a negative electrode from ERC. And the separator in two of the cells was potassium titanate and in two of the cells it was nylon.

The test cycle we ran was a 3-hour cycle. We charged for 1.8 hours, discharged for 1.2. The depth of discharge was 85 percent. Now, when I say 85 percent, it was 85 percent of the measured capacity on the first cycle that I measured on these cells to one volt. So there is no de-rating or anything here.

Okay. The next slide will show a comparison between the titanate separator and the nylon separator.

(Slide 189.)

On this viewgraph you see down at the bottom here the discharge time in minutes, and the cell voltage along here.

1h74

This cycle here was the cycle number 1322. Now, what you see here is a slight more polarization with the KT separator. It's about 30 to 40 millivolts, and you see the normal discharge down to -- take them all the way down to a tenth of a volt.

Okay. The next slide will show the cycle life of a cell with a nylon separator.

(Slide 190.)

Once again, the discharge time along the bottom and the cell voltage along the side here. Now, the top curve, this was for cycle 167 and the bottom was for cycle 1329. There isn't too much of a degradation there, and what you see here is a slight increase in the capacity with the 1329th cycle, the capacity, that is, to a tenth of a volt.

I do have another cycle that I ran, or another discharge at about 850, and what you see, the capacity is way out here. Normally what it will do in all the cells, it will start -- we are talking about capacity to a tenth of a volt now -- start here and grow out to here and drop back somewhere in between.

All right. The next slide shows the KT separator; again we see cycle 160 and cycle 1322.

(Slide 191.)

There is very little degradation here, as you can note.

Okay, the next slide shows another nylon cell, with a nylon separator, that is.

(Slide 192.)

There were two of each. I already mentioned that, and I show this particular cell because it was the first one that fell. Now here we see it up here at cycle 1329, and it's showing a little more degradation than the other nylon cell showed.

Now, that cell continued to run to about 1500 cycles where the voltage just all went to -- it just dropped down something like this. I took the cell out, and I measured the impedance, and it had grown from about 56 milliohms all the way up to somewhere in the neighborhood of about 200 milliohms.

What I did then, I just let the cell sit overnight, and strangely enough, the next day the impedance was up to 4 ohms. What I did then was -- this happened last Thursday.

NI-H₂ SUMMARY

POSITIVE	SAFT	GOULD	ERC	SAFT
NEGATIVE	PT	PT	PT	PT
SEPARATOR	NYLON	ST	KT	ST

↑ STACK ASSEMBLED BY
COMSAT
FIGURE 187

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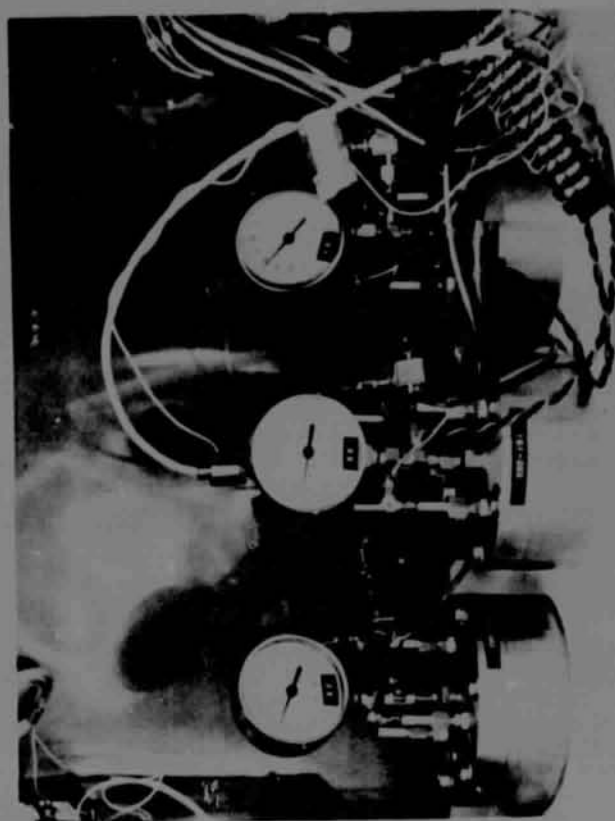


FIGURE 188

NI-H₂
I₀ 13A

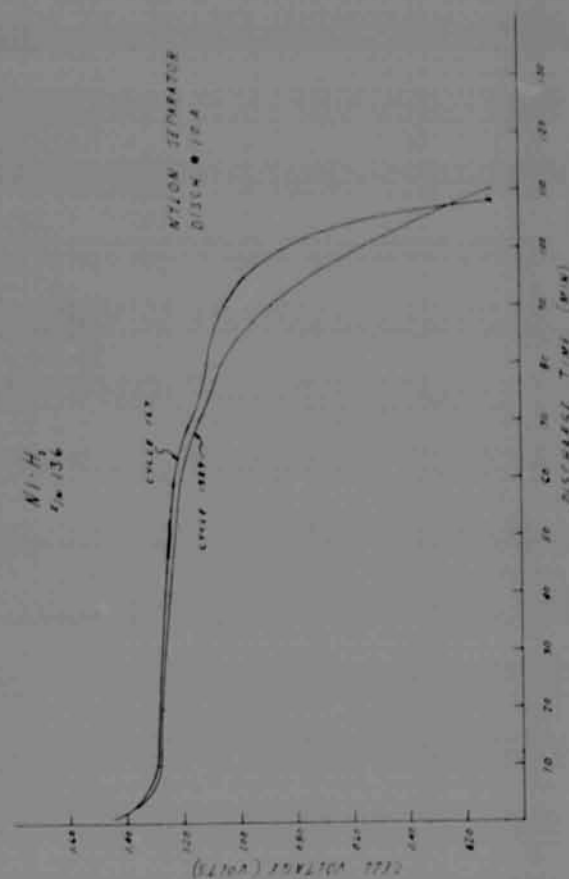


FIGURE 190

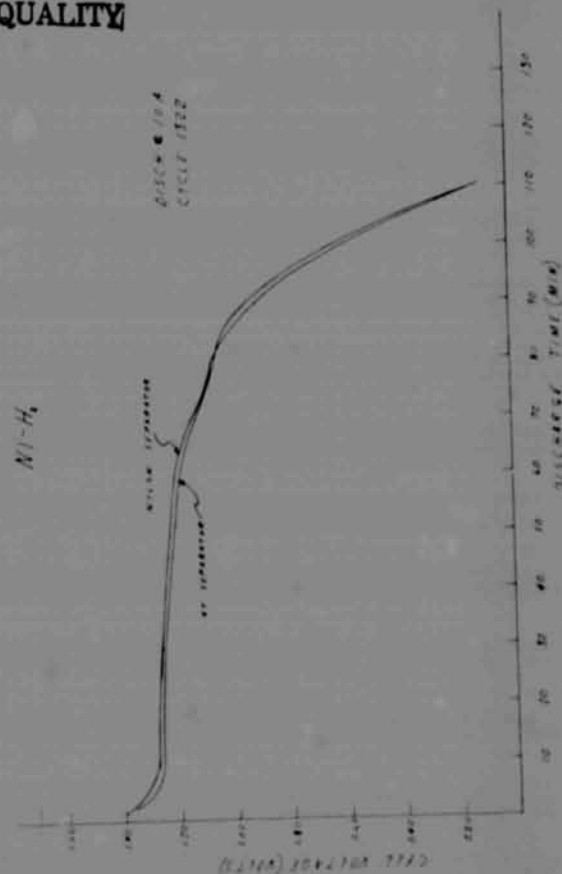


FIGURE 189

1h75

I haven't taken the cell apart yet, but I did open it to look in it, and it did appear that the separator was dry and the positive electrodes had swollen considerably. So it looked like the electrolyte indeed was pushed out of the cell.

Okay. The next slide shows a performance of a larger cell.

(Slide 193.)

.... This is a 50 amp hour variety. This cell had the back to back SAFT, 1 millimeter thick, or 40 mil thick positive, has nylon separator, and had a platinum negative electrode from Energy Research. And it was built similar to this here stack I showed you, compressed on the ends with plastic end plates and run in a boilerplate.

Once again, the bottom is the discharge time, and alongside here is the cell voltage. This shows cycle number 54, and down here it shows cycle number 615. This cell was cycled at a 65 percent depth of discharge, a three hour cycle again, charge 1.8, discharge 1.2, and the discharge current here, as you see, was 25 amps.

Unfortunately, the cell only ran to about 800 -- about 900 cycles, and the end of discharge voltage at 900 cycles was just about right here. What happened there was that the temperature chamber went screwy on us. It happened to be 6 o'clock on a Friday night on a 3-day week end that the temperature chamber decided to go hot and it got up to the neighborhood of 150 to 175°C.

When I came in Monday morning, they were opening the cell up. There wasn't any separator to be seen anywhere. So I was kind of disappointed that happened. That cell was running very well.

The overcharge in the cell, by the way, was 10 percent, and the overcharge on the smaller cells was 15 percent. Interesting enough, to bring out a point here, is the failure mechanism on these cells.

People have been sort of scared of explosions and this type of thing. Now, when this cell failed, what you generally see is a rapid decrease in cell pressure and accompanied by a rapid decrease in the terminal voltage. By no means do you get an explosion.

And I had another one, another 50 ampere hour cell, that I made with uncoined raggedy electrodes. -- I tell you they were raggedy -- and it ran close to a thousand cycles where I did get a short on the outside of the cell. And once again, it didn't explode. It behaved in the manner so

1h76

described here with the pressure decreasing very rapidly. Okay, let me see what I have next here for you.

May I have the next -- final slide?

(Slide 194.)

Oh, this slide, I have always heard people ask me this: how about the self-discharge of these nickel-hydrogen cells? So what I did, I took that 50 ampere cell when it was brand new, and I did measure the self discharge by, of course, charging it up and letting it stand for a certain amount of times and discharging it all the way down to a tenth of a volt.

This is the capacity to appear at the capacity remaining to a tenth of a volt, and down here is the open circuit time, and I let it run out to somewhere around here, 72 hours, three days. And what you find is about the end of three days you lose -- you have about 65 percent of your capacity remaining.

This is a homemade log scale, supposed to be a log scale up there, you can believe that. Well, that's about all I have. Thank you.

DUNLOP: Any questions?

STEINHAUER: I have three questions. Is there reason for using positives back to back, second is the plateau positive related, and third is there any -- are any measures taken to maintain mechanical pressure on the plate stack?

STOEKEL: The first question, why used back to back. The reason for that is to increase the energy density, to get more active material.

STEINHAUER: As contrasted to, say, using a 60 millimeter single plate?

STOEKEL: That's right.

DUNLOP: Let me answer that. We went through a program with SAFT to see how thick they could make a plaque with the normal slurry process, and they went through a very nice study on that, and the limitation was about 40 mils. To go much thicker than that in the slurry process, they start getting a large variation in the thickness of the plaque.

Now, that is the answer to the thickness of the sinter plaque. It turns out that the reason we use them back to back is to increase the energy density and to get a thicker electrode. And it turns out that this means that we

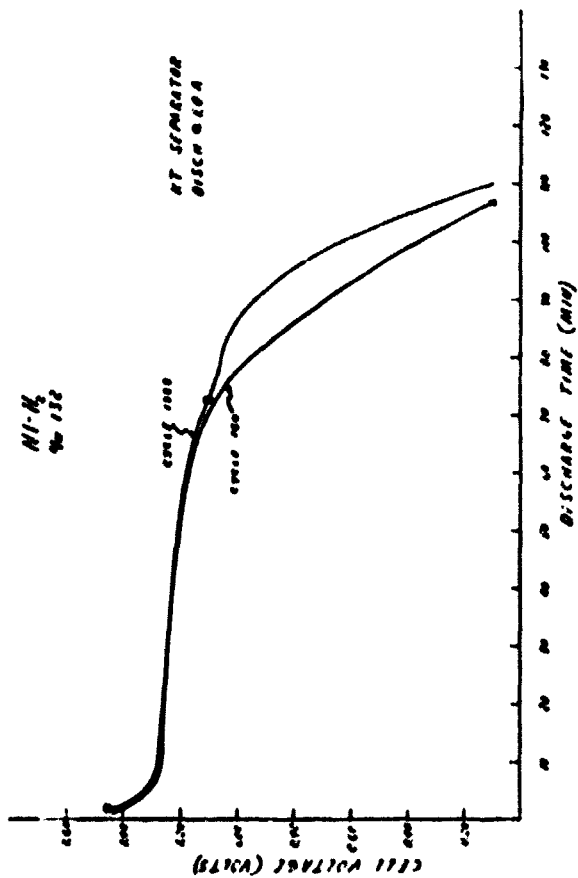


FIGURE 191

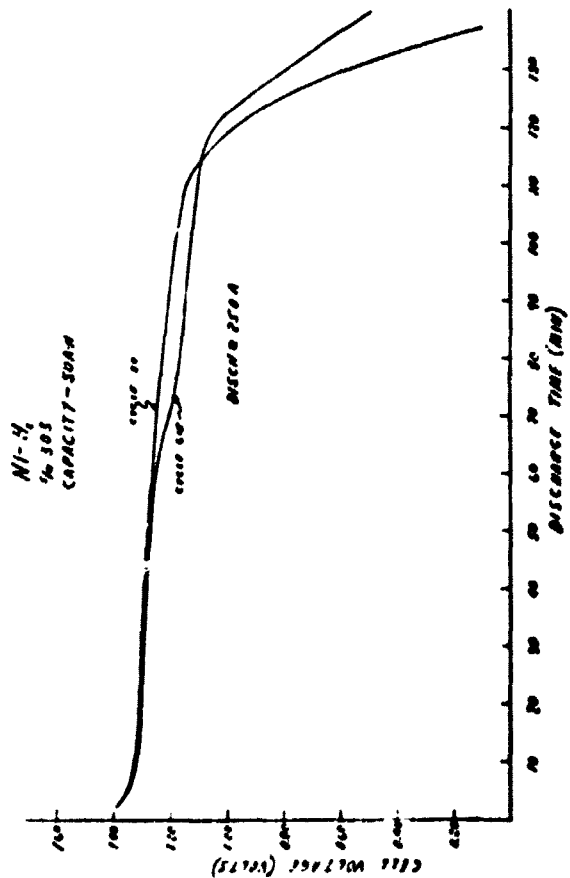


FIGURE 193

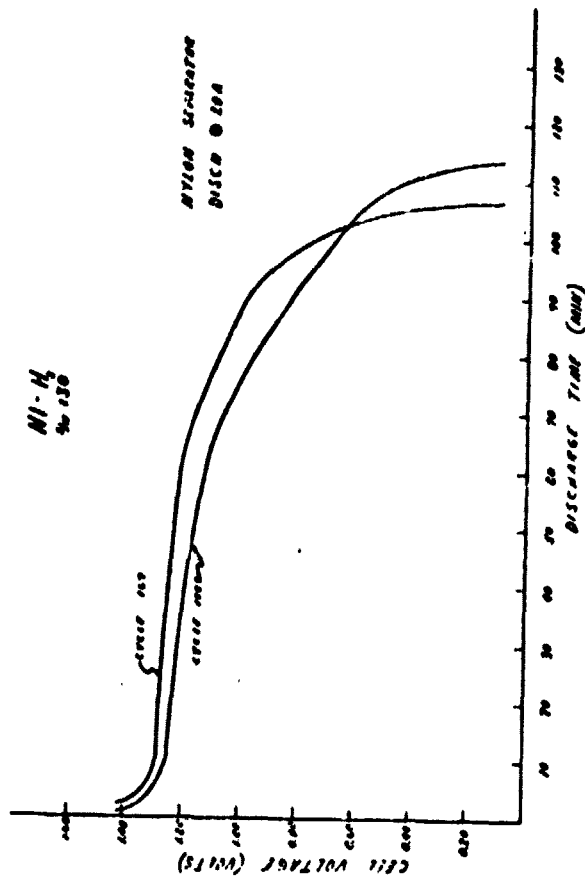


FIGURE 192

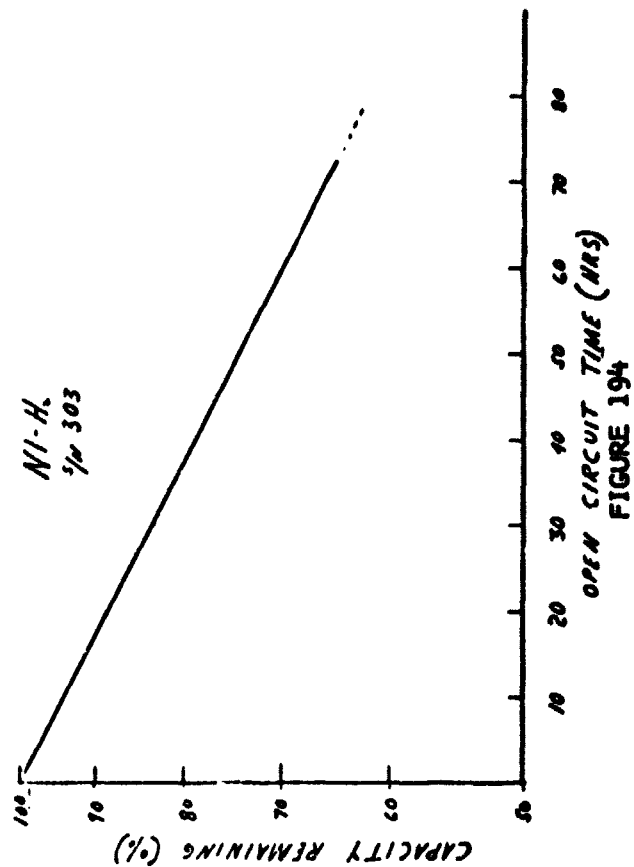


FIGURE 194

1h 77

really have an 80 mil thick electrode with these two 40 mils back to back.

We find -- we actually make flooded measurements of these electrodes as individual electrodes prior to assembling in the cell. When he put that 50 ampere hour cell together and he measures that total capacity, he is talking about 95 to 96 percent of the capacity he was able to measure flooded.

So the utilization at the rates that we are using is excellent with these thick electrodes, using them back to back, and we can't make them in the sinter process with the slurry process any thicker than 40 mils.

STEINHAUER: Plateau -- is the positive plate related?

STOEKEL: Yes.

STEINHAUER: Do you use any attempt in controlling the mechanical pressure especially on the separator?

STOEKEL: Yes, you can see it here. That's what the endplate is for here. Right now I am just using a threaded rod with screws, nuts on the end. And I have been fooling around with the optimum squashing.

STEINHAUER: It's a fixed set rather than a spring loading?

STOEKEL: That's right, there is no spring loading.

KRAUSE: What operating pressure have you been running at on the hydrogen?

STOEKEL: This pressure runs, with this particular cell here, will run up to about 600 psi.

KRAUSE: Is that what they have been running on your tests?

STOEKEL: Yes -- no, the smaller cells ran from 250 to 150, and the boilerplate cell ran about 600 to 250, something like that.

KRAUSE: The other question I had was whether or not you have seen any water loss from the stack, and if so, are you taking any steps?

STOEKEL: Yes, you do. When I make a cell I put it together in the boilerplate, and I draw a vacuum and bathe the entire cell with electrolyte and let it sit overnight until it's completely flooded. And I take it out and pump the electrolyte out and towel dry it, and the first

lh78 couple cycles electrolyte will squeeze out of the stack.

KRAUSE: That's the only specific thing, specific design?

STOEKEL: Yes -- you mean such as entrainment in the gas?

KRAUSE: You are not putting any linking in there?

STOEKEL: No, no tricks. Just straightforward so far.

HAAS: I noticed on your open circuit data you are showing a reduction in pressure. On what size cell were you evaluating there. And two, what was the type of separator that was being used in that cell?

STOEKEL: That cell was the 50 ampere hour cells that I had shown in the previous slide. It had the nylon separator. And what was the first question?

HAAS: I think that covers it. One other point, have you seen other discharge rates utilizing different separators?

STOEKEL: No.

GASTON: The last 12, the self discharge which you showed, at what temperature is that true?

STOEKEL: Twenty-three degrees centigrade.

GINTER: I would question the linearity. I think it is very slow. It is not a straight line.

DUNLOP: It was supposed to be logarithmic but he made a sketch.

STOEKEL: I said it was a homemade log plot.

GINTER: It levels?

STOEKEL: Oh, definitely.

FORD: Your discharge voltages are very similar to some we experienced with NiCd's. And all your reference so far is to the ampere hours to a tenth of a volt. But what I find interesting about the discharge profile, that if you look at the total area on the curve with the data you have shown the apparent energy storage is an approximate thing.

Every time you get a pressure with discharge

1h79

voltage you see a slight increase in the capacity. Have you thought about looking at the energy storage relationship with cycle life on these cells to complement the ampere hour data that you are getting?

STOEKEL: No.

FORD: That's a suggestion. I think you will be interested in it.

STOEKEL: Thank you.

BILLERBECK: Billerbeck, Comsat. I still hear a few comments about safety. You might want to comment again, as he mentioned in other papers, about the pressure and what limitations you get on the pressure, and what sort of personnel safety aspects are there.

STOEKEL: Okay, Bill. I got so saturated in showing some of those slides with the electrochemical reactions and the profile of the pressure as you charge the cell. I thought everyone would have known about them by now.

But anyhow, what Bill is saying is, as indeed you do charge the cell, when you get to overcharge you generate the oxygen on positive electrode and it very rapidly recombines with the hydrogen on the negative. And there is no danger of overpressurizing the cell.

The same thing with reversal, when you get down, run a cell in the reversal, you get hydrogen being generated at the positive and then it's again used up at the negative. So it's a very stable system.

KRAUSE: Doesn't the combination of the oxygen overcharge with the hydrogen tend to have a tendency toward a thermodynamic system there?

STOEKEL: No, we have never seen -- what you see, yes, the temperature of the cell definitely will increase on overcharge. And it's very much dependent on the rate.

DUNLOP: As a matter of fact -- let me just make a comment, the argument of stability. We continuously overcharge for days at a C rate on these big cells, for example. Of course I don't recommend that that's a good idea, but there is every indication that you have an overcharge capability at least four times greater than you do in a nickel-cad cell when you have ample cadmium for overcharge protection.

Now, there is an interesting point here that hasn't been brought up yet either. When you cycle a cell in none of the modes that are described do you make or consume water. There is no net buildup or loss of water in the electrolyte in cycling a nickel-hydrogen cell. There is in a nickel-cad cell.

1h80

And therefore, you never become, in this cell you never become negative limited on charge. There is no way to ever become negative limited on charge in this particular cell.

KRAUSE: Would you expect a reaction to a curve with the oxygen-hydrogen recombination if the platinum was dried out and exposed, so to speak.

DUNLOP: You are making water at that surface. By the way, you know the partial pressure of oxygen that we normally observe, we can't even, at those rates, we never see more than a partial pressure of 1 percent oxygen. And even, by the way, when we are running at these 100 and 200 psi to take gas samples, it is almost hard to find the oxygen. A very low portion of your gas in there is oxygen.

The fact that we ever run the hydrides is also a good indication that there is a very low amount of oxygen showing up.

WARNOCK: Warnock, Air Force. In these cells where you have a stack of hydrogen that are not in very good thermal contact with the case, have you measured the temperature rise on the stack with respect to the case, and what are the implications of that temperature differential for driving water out of the electrolyte?

STOEKEL: Yes. One time, a year and a half ago, I made a 25 ampere hour cell and actually put thermocouples into the stack. And it just performed exactly like I expected. It increased on overcharge, increased slightly on discharge, increased very rapidly as the thermovoltage fell off, and when I got into reversal the temperature then returned to normal.

And hydrogen, again, is a very good, is an excellent thermal conductor.

.....
HOLLECK: Tyco Labs. What were the temperature differentials?

DUNLOP: Let me answer. We actually presented that data in this paper that Dr. Giner and I gave, and will come out one of these days in the literature. Actually Tyco made a cell similar to this, but the temperature difference is during the normal charging or actually there is no difference.

The cell is not dissipating any heat at all, but once you go in the overcharge range you run about 10 degrees higher. I think it was a C rate or a C/2 rate. We are only running about 10 degrees higher in the center. That was the hottest temperature, the center, than we were at the case.

1h81

Now actually the highest temperature shot up when we went into discharge, we got a slight peak when we went into discharge, then it dropped off. And in reversal you got very little heat dissipated, see a very low temperature in reversal.

GINER: One of the problems of the nickel-hydrogen cell you see -- with electrolyte -- I don't think it's as much as the water problem, because it's true it is hot on the inside but the vapor evaporates more. So you evaporate more, the pressure gets higher, the driving force is the other way out.

I think the problem may be gassing while charging. You may splash out the electrolyte, but there are some indications that when you observe the performance if you put in electrolytes too you will recover the performance.

DUNLOP: We didn't show this, but we have other smaller cells that have run up to 8,000 cycles now, and in those cells we did have a variety of parameters, which again were reported. But one of the variables was the type of electrode that we used at the hydrogen electrode, and when we didn't use a hydrophobic type electrode we did lose electrolyte by gas entrainment and we did see drying out.

GANDEL: Gandel, Lockheed. Going back to this question of overpressure and danger of explosion, I would just like to make the comment that you were talking about an aerospace lightweight design cell, working with a safety factor of maybe 2 to 1 instead of a conventional 4 to 1 or more.

And going back to nickel-cadmium, you are operating on a safety factor more like 10 to 1 on that kind of cell. So in the event that you did have a failure of a weld or a seal, and you have a pressure vessel at four or five hundred psi, if that thing at that point lets go you have a bomb. I don't see how you can forget that.

DUNLOP: Why won't the gas just leak out? Why is it a bomb? The gas just leaks out.

GANDEL: If it comes about gradually. But if it decides to rip.

DUNLOP: Okay.

STEINHAUER: What is your current degree of interest in this storage -- is that still active?

DUNLOP: Very active, for a lot of different reasons. I am not sure whether they are the right reasons or not.

1h82

KRAUSE: I was wondering, Jim, if you have done any measurements or intend to do any measurements on magnetic property of the cell, and whether or not it will be comparable to NiCd's.

DUNLOP: We haven't done anything on the magnetic properties. I am sure that Klein would like to answer that question.

KRAUSE: The other question I have is whether or not we expect to see any electrolyte management problems on the spacecraft.

DUNLOP: A good question. There is a very active program right now to start looking at these things. By the way, I don't want to deviate too much on these things, because we don't know the answer yet, so we will be getting this kind of information in the near future.

There is an argument here that maybe substantiates the use of potassium titanate also.

GINER: I wanted to comment again on the two steps that you have shown in most of your cycles. You see the two steps at the cycling, and then you can remove the second steps, sometimes.

DUNLOP: By reconditioning all the time. That's a good point.

GINER: All the time. The memory effect, I don't doubt this is due in part to that, but the nickel-hydrogen cell is very good because it allows us to set a nickel electrode separately.

DUNLOP: Right. I was going to make a general comment on that very point too, so I am glad you brought it up. Based on some of the discussions that came out this morning, to augment what Dr. Giner just said, in a nickel-hydrogen cell the hydrogen electrode is extremely stable. And the polarization losses that you see at that electrode are very small.

For the current densities that we are operating this particular electrode, which are still under 20 milliamps per centimeter squared, this is in a very stable electrode. Therefore, what you observe, in terms of the performance data up here, is probably a much better check on how the nickel electrode behaves than any of the data that is probably presented on a lot of testing that is done on nickel-cadmium.

The point I want to make there is that we do not see in our high-rate cycling this kind of an effect, absolutely do not see that.

1h83

STEINHAUER: Jim, on your cell where you do see that double plateau and you are reconditioning, does it recur sooner?

DUNLOP: I don't know, Bob. Unfortunately, we don't have a lot of data on that right now, but Joe's tests he usually does it about every 100, 200 cycles, and I don't think he brought some of that data with him to show that effect.

STOEKEL: No. I wait for 200 cycles before I can measure the capacity. But you do see the expected increase in voltage on the subsequent cycle that rapidly drops off, say in 40 or 50 cycles.

STEINHAUER: That's not diminishing in terms of number of cycles before it occurs at the end?

DUNLOP: I don't know. We don't have a lot of data on that. One thing should be said in addition. Joe pointed out the work we are doing. See, we are also finishing up a program with Tyco, and they have another can design slightly different than this. That is quite good, too. It's made from Inconel, and we will be finishing these cells and testing them shortly too with a stack very similar to the one Joe showed.

BILLERBECK: Billerbeck, Comsat. You mentioned a separator. There was no electrolyte in the separator. Were you able to see where the electrolyte was?

STOEKEL: No. I haven't taken the stack apart yet. It appeared to be very dry from just looking and feeling it, but I haven't taken it apart.

LANDER: What is the highest average on your cycle time, of its temperature on your cycle time?

STOEKEL: Extended cycle testing has been done all at room temperature, 23°C or so.

DUNLOP: We have done some high temperature testing but mostly for performance, not continuous cycle

HELLER: Heller, Hughes. What margin does your present pressure vessel design allow for?

STOEKEL: That one I showed you right there burst at 1500 psi.

DUNLOP: We will go on to the next one. Thank you very much.

1h84

I would like at this time to introduce our next speaker, who will be Marty Klein from Energy Research Corporation.

KLEIN: Actually, this is pretty similar to what Joe spoke, so we will run pretty quickly through it.

Can I have the first slide?

(Slide 195.)

This is a section of the 50 ampere hour cells we will be delivering to Comsat, using the same can that Joe showed you. Our stack construction is a little different, and we are using plastic endplates and tie rods around the outer diameter of the electrodes. And a number of these tie rods actually come down and are welded to the bottom zone to lock the whole stack in place.

And we bring wires directly out of the respective electrodes, the hydrogen electrodes with nickel wires out this side, the nickel electrodes the other way, through insulated feed through terminals.

In answer to a couple of questions that came up, on the thermal situation, is that you have virtually no locking, thermal locking of the stack to the can. And the heat transfer is along the plane of the electrodes, which is very good in this direction because the electrodes are stacked this way. And then the heat has got to jump the hydrogen gas. It turns out that hydrogen is quite a good thermal conductor.

Our measurements show about, well, of course it depends on the rate. The worst case heat transfer situation is when you are overcharging at high rates, so you have to lock a temperature difference dependant on the rate at which you are generating the heat.

For a typical 25 amp discharge cell, there is about a 70°F Delta T between the center of the stack and the outer wall. If you take the heat away, you are okay, because with the electrolyte concentration 30 or 35 percent, I think in order to get condensation you have to have a Delta T of about 180°F before condensation will occur due to vapor pressure differences.

Can I have the next slide?

(Slide 196.)

This just shows a nickel electrode with the wires.

Next slide.

1h85

(Slide 197.)

What we do is we make an assembly that consists of a nickel electrode as previously shown with the separator material of the same size. And we use a heat shrunk tube to laminate a layer of the separator on either side, and this gets us away from this edge shorting problem, plus it makes it easier for the assembly of the stack

As far as the separator -- the point came up yesterday and let me talk some more about that. At the outset of our nickel-hydrogen investigation, we felt that the criteria for the selection of the separator is somewhat different than even conventional nickel-cadmium cells.

You are evolving hydrogen, and there are possible problems that, as the gas evolves, you can have electrolyte entrainment into the gas. So we thought (a) you would want a separator material that had much better capillary holding characteristics than the conventional nonwoven materials. Also it's pretty nice to have material that's more chemically stable than the nylons or polypropylenes.

We came upon using this potassium titanate, which we make ourselves, and it is a material that runs about 7 mils thick. It is slightly more resistant than nylon, as Joe's data showed on the life testing. However, from what we have seen, it is completely chemically inert and has very good electrolyte retention characteristics, and it has enabled us to run cells well over a thousand cycles and with no electrolyte loss.

Can I have the next slide?

(Slide 198.)

This shows the hydrogen electrode that we developed for this cell, and it is essentially the same electrode that all the data that Joe presented employed. Here too, there is some concern, and there is a right way and a wrong way

Can I have the next slide?

(Slide 199.)

The back of our hydrogen electrode contains a micro-porous layer of Teflon, and this turned out to be a very important feature of the whole electrolyte management aspect. You have the hydrogen gas is evolving on the platinum face to the electrolyte separator. If you have a material like nylon, which has a rather open pore structure, actually the gas will bubble through along the front face of the hydrogen electrode between the nickel electrode and the hydrogen electrode.

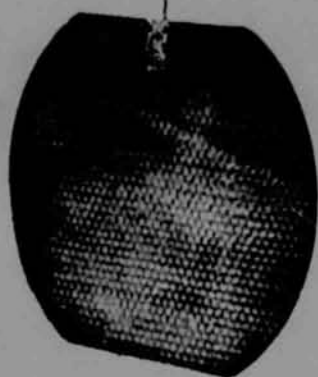


FIGURE 196

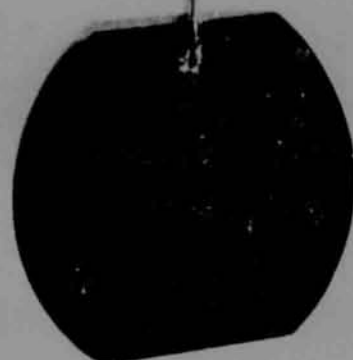


FIGURE 198



FIGURE 195

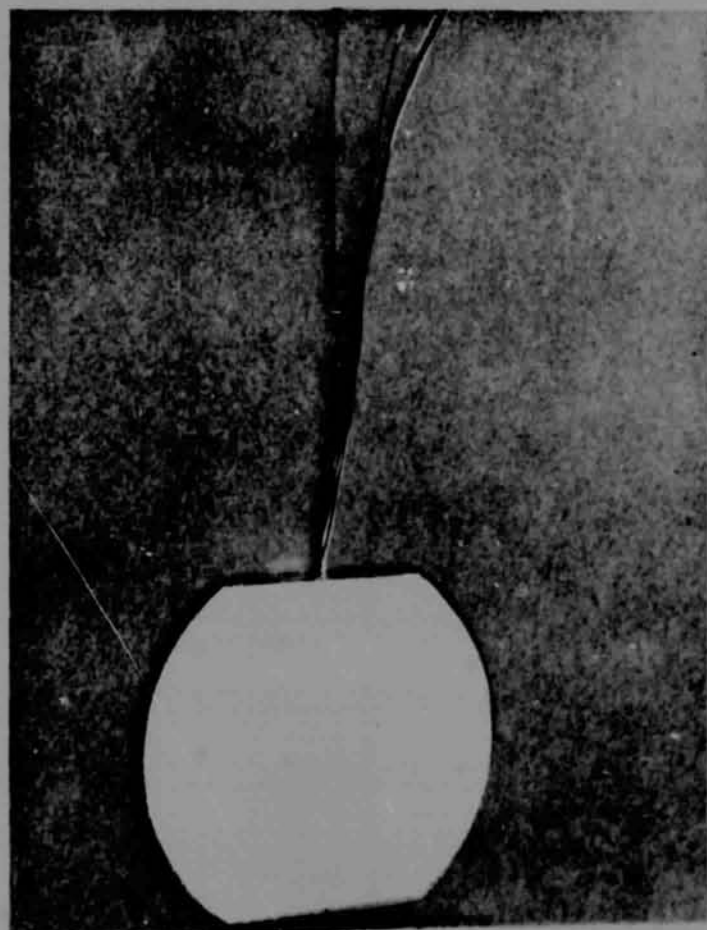


FIGURE 197

1h86

If you use a separator material like KT, which has a much finer pore structure and essentially a high bubble pressure, the gas actually finds its path of least resistance by bubbling out the back side of the hydrogen electrode, which is what we prefer.

And then we put this porous layer of Teflon on the back, which acts as a further filter to stop the entainment of any electrolyte. And we have shown that if you remove the Teflon backing you can show that you will have electrolyte loss and cells will deteriorate.

With this we have never gotten electrolyte. So it is a combination of the hydrogen-electrode structure and the separator material that we think is very important for the electrolyte management. And the whole thing has to work together really.

Can I have the next slide?

(Slide 200.)

This is just a gas diffusion screen that we place on the back side of the gas electrode to allow gas in and out of this back readily.

Next slide.

(Slide 201.)

And this just shows the sequence of the three components as we stacked them up.

Next slide.

(Slide 202.)

This shows earlier what I described the anchoring of the stack on the bottom dome.

Next slide.

(Slide 203.)

This is actually the 50 ampere hour stack, and we are using plastic compression seals of the Ziegler type as shown here. What we do is we make a connection between the rods and the wires.

Can I have the next slide?

(Slide 204.)

This is the plastic compression seal.

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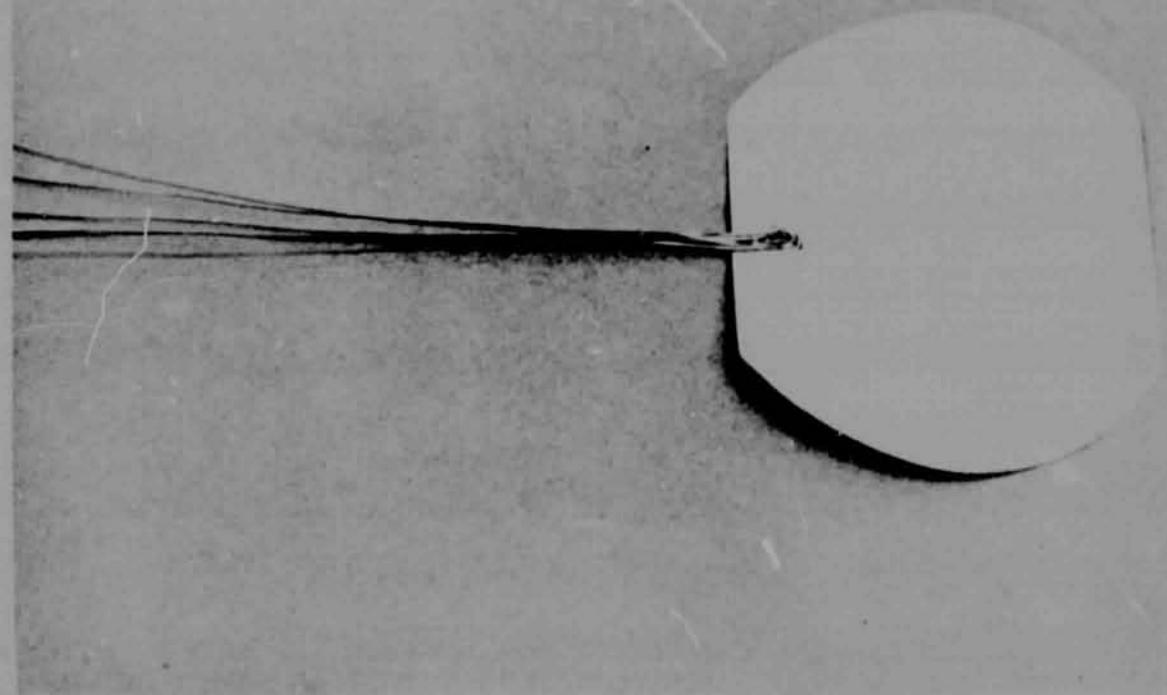


FIGURE 199

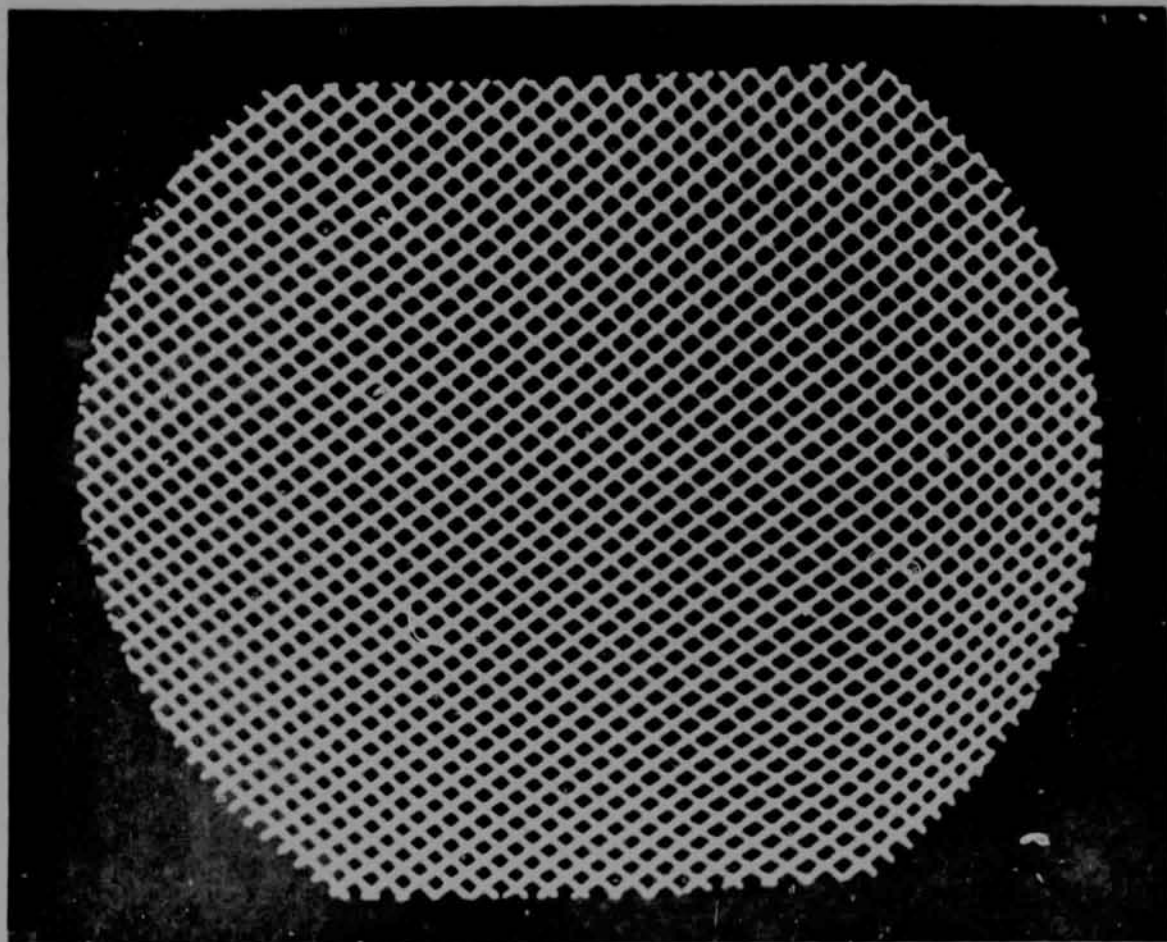


FIGURE 200

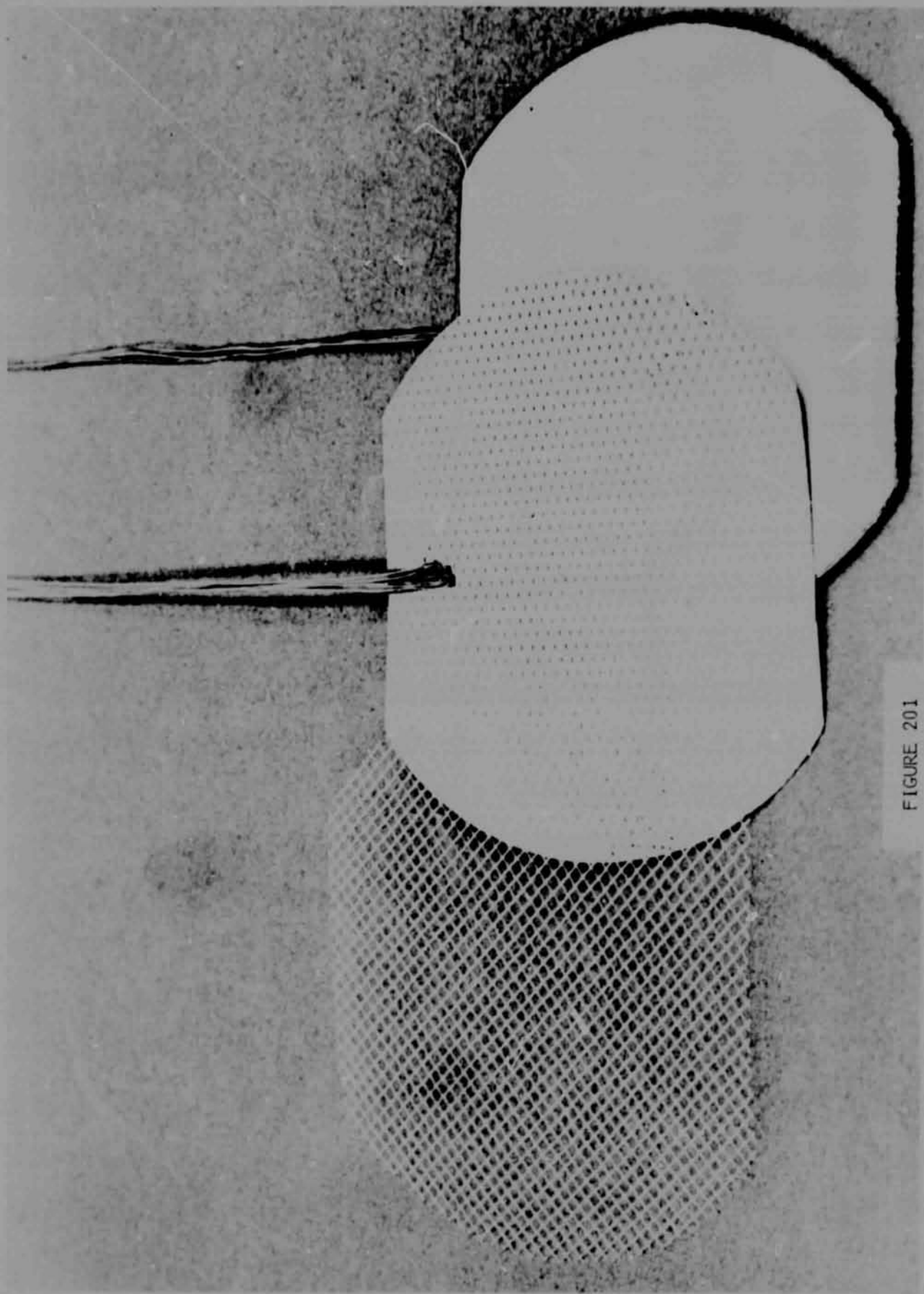


FIGURE 201

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1h87

Next slide.

(Slide 205.)

And this shows just the finished 50 ampere hour cell with in this case a pressure transducer on the top for monitoring pressure.

Next slide.

(Slide 206.)

This, as Joe mentioned, actually in our second program we have with them we are starting to look at the environmental capabilities of the cell and the structure, and we are just actually starting this work now. This just shows a cell mounted on a vibration fixture.

Next slide.

(Slide 207.)

This is our, I guess, it's our zero G vibration test, right? Minus one G. You haven't got it yet. Okay

Can I have the next slide?

(Slide 208.)

This shows some of the data that we have. We have a variety of different data. Actually, this probably represents the longest life. This is a single electrode test similar to the test cells that Joe showed, except it's of the same diameter that's used in the 50 ampere hour test cell. What we were doing here is running a six hour cycle, a 1.2 hour discharge, 4.8 hours of charge, so that's four cycles a day.

We are out I guess 1300 cycles or so, a little short of a year continuous cycling. And there is some fall off in the end of discharge voltage, what is shown here, but it still runs pretty well. The operating voltage level here is somewhat low, but this is really caused by the way the terminals are put in this single cell, and there is a high IR drop just in the terminal so it's really not representative. It should be up here without that IR in the terminals.

Can I have the next slide?

(Slide 209.)

This shows similar data for a 50 ampere hour cell that we had on test, also on the same test conditions out past 600 cycles.

Can I have the next slide?

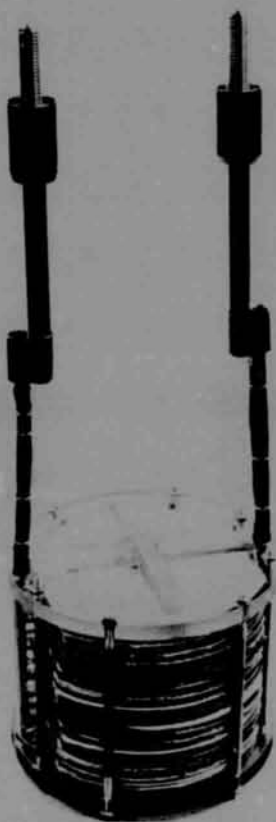


FIGURE 203



FIGURE 205



FIGURE 202

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FIGURE 204

1h88

(Slide 210.)

We now, in conceptually the same approach, we are now building some 20 ampere hour size cells which will be based on a two and a half inch outside diameter, and this shows the prototype stack of that version. Conceptually the same materials, the same design.

Can I have the next slide?

(Slide 211.)

That's just the cell with the can. I think that is the last slide.

STEINHAUER: Steinhauer, Hughes. You avoided the center tie rod. Is there a reason for that? Secondly, I don't see the second plateau. What happened to that?

KLEIN: What I showed in data here was end point voltages at the end of my 60 percent depth cycle, so that's why it is not there. Maybe I went too fast. I was trying to get out of here tonight. I am sorry. Now what did I avoid? You lost me.

STEINHAUER: The center tie rod.

KLEIN: Oh, the center tie rod. I have a tendency to feel that you have a structurally more stable arrangement by putting a ring of tie rods around the outside. And we will be looking at both of these things. We have these cells of the two types, and we will decide, I guess in the next generation, mechanically which way we prefer.

STEINHAUER: Is there a weight disadvantage to doing what you did?

KLEIN: I don't know. I don't think there is much difference one way or the other on a weight basis.

FORD: Have you measured the expansion of the positive plates -- is that the message?

KLEIN: Yes, we have done some of it, not a lot, and it varies. We are working with a variety of different nickel electrodes in testing them, and you can see 20 percent volume expansion, thickness expansion, on some nickel electrodes. And the way it works out, we are not using any springs on the stack in the things we are now doing.

What we observe is that we have this gas diffusion screen behind the hydrogen electrode, which is about 18 mils thick, and the positive electrode expansion actually with KT, which is sort of soft material, actually pushes the entire KT and the hydrogen electrode into the convolutions of the

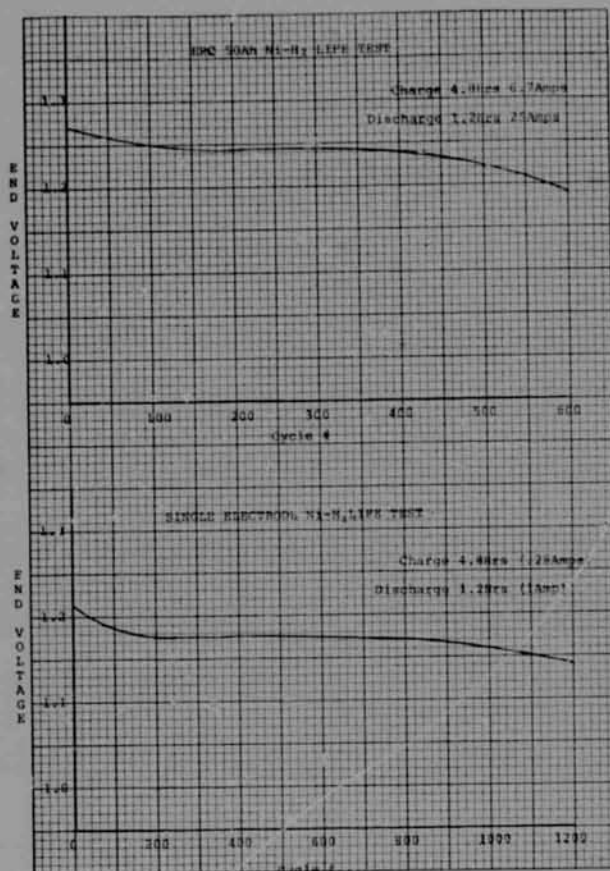


FIGURE 208

FIGURE 207 NOT AVAILABLE

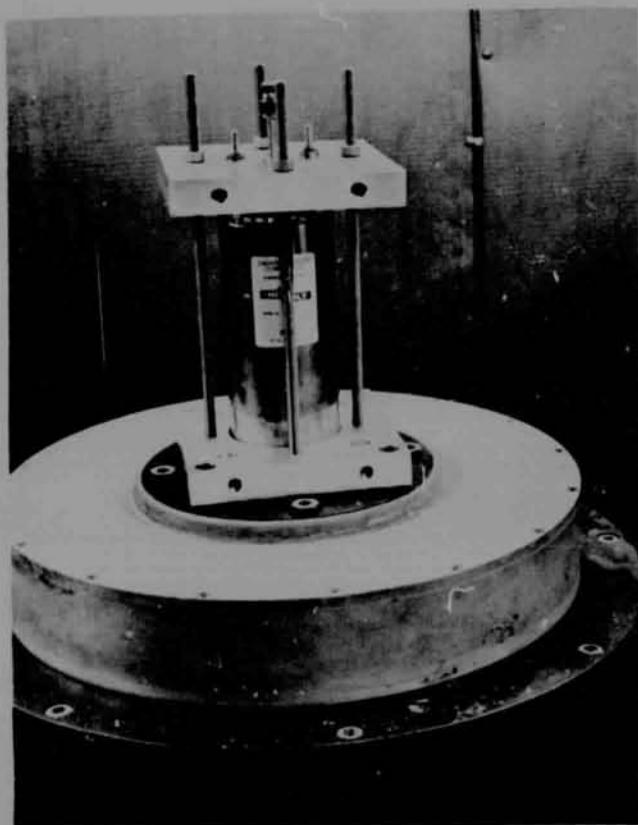


FIGURE 206

FIGURE 211 NOT AVAILABLE



FIGURE 210

FIGURE 209 NOT AVAILABLE

Vexaw gas diffusion screen which we actually think is a good thing because that allows for the sponginess and for this nickel electrode expansion.

But I think that is going to be the next real question. I think we really have a stable hydrogen electrode, and we have run it for a long, long time and see no problem. I think KT, what we are doing now, you know, I have tremendous confidence that that's stable. And really the next question that we are working our way toward, certainly a thousand cycles looks pretty good but under these test conditions. If we start going out, I think we would have to go back and look at the nickel electrode, the whole question of how thick it should be, what the relative loading in the pores relative to the plaque, and some of these other questions.

And we really haven't done enough yet.

WARNOCK: Warnock, Air Force. Can you comment on what consideration you have given to battery configurations and concepts for large items?

KLEIN: I have done very little in that area myself. There are some aerospace battery system people that are looking at this at this point. I am not able to comment on that just yet.

HAAS: I was going to ask a similar question. You are currently measuring energy in the order of 25 watt hours, perhaps a little better or worse. What decrease in the energy density might you expect from packaging in an assembly for some applications?

The second question: You indicated a temperature gradient between your cell stack which is apparently -- I am not sure if you measured it -- at the center of the plate. Did you also measure the temperature at the top of the can where you are not really dissipating heat through directly?

KLEIN: Yes. The top of the can, well, I don't remember. The top of the can is in between. If you are taking the heat out, it depends on what you are using as a heat sink.

HAAS: Radiating, I would assume?

KLEIN: If you are radiating, let's say, in a blowing environment. See, you are taking the heat out. The top of the can probably runs about 3 degrees cooler than, you know, opposite the stack.

HAAS: Are the degrees up?

KLEIN: Yes, substantially, as long as you are taking it out.

1h90

HAAS: There was a question on the packaging.

KLEIN: Yes, on the packaging. These cells will be running in the 25 watt hours per pound. I think that's not the last word, you know, and we would expect to go up 30, 35. If you take 25, I don't know what the penalty is going to be in packaging. I think it has a lot to do with how you put it in.

Each cell physically is structurally, you know, self supporting. It is a question of how you egg crate it. That is really a little out of our lead.

HAAS: Is it a value of about 10 percent of the proposal?

KLEIN: Yes, I think that's reasonable. I'll take it.

GASTON: Gaston, Grumman. What is the overall volume of the 50 amp hour cell and what's the weight?

KLEIN: The overall volume is a tough one.

GASTON: Give me diameter.

KLEIN: Three and a half inches in diameter and to the top of the dome seven and one and three quarters. It is eight and three quarters to the top of the dome, and three and a half inches in diameter. Is that right?

DUNLOP: Something like that. That's pretty close.

KLEIN: And the weight -- Joe has a better number than I have.

STOEKEL: The volume is about 1100 cubic centimeters. The stack takes about half of that.

DUNLOP: I think we are going to move along then.

KLEIN: I would like to acknowledge the support of Comsat for a major portion of the work presented.

DUNLOP: Our next speaker today is going to be Earl Carr from Eagle Picher, the same subject.

CARR: The purpose of my talk is to briefly present Eagle Picher's metal oxide hydrogen battery program. We initiated our hydrogen battery program, as is pretty obvious, because of the strong promise of this high energy density, long life, rechargeable system. We are directing our immediate efforts toward attaining nickel-hydrogen cells with an energy density of 31 w-hrs per pound, and a life expectancy

lh91

of greater than ten years; and our silver-hydrogen cells of 50 watt hours per pound with two to three years' life.

Our work has been conducted for the last year, and it is based on our existing technology in metal-air, nickel-cadmium and silver-zinc batteries. The first thing on our initial work was company funded and was directed toward silver-hydrogen. But the major emphasis of our internal program and our funded effort has been in nickel-hydrogen.

The first program resulted in the development of a 20 ampere hour nickel hydrogen cell, with an energy density of 26 to 28 and a half watt hours per pound. This is shown in the first viewgraph.

(Slide 212.)

Our program involved determining performance characteristics and cycle testing of this cell. I don't have slides on charge-discharge data, but it is very similar to that which you have seen. The one thing that we noticed is that typically the voltage levels are approximately 50 millivolts better than nickel-cadmium under the same conditions. This is really quite a nice point.

Our cycle test program on this cell, or on a similar prototype cell, has accumulated more than 2,000 cycles without any noticeable problems. Our first contractor funded program was initiated in June or slightly later of this year, and it is for the development, as Joe Stockel presented, of 50 ampere hour INELSAT related nickel-hydrogen cells.

This program will be for the development of both prismatic and cylindrical 50 ampere cells of a flight configuration, or let's say a flight type configuration. The cells during their development will be tested dynamically as qualification level testing.

The program consists of computer optimized geometry, parametric cell design, and dynamic testing, as I mentioned. Okay. For the computer program we made certain assumptions. The computer program was set up based on assuming an operating pressure based on previous Comsat work that will be in the order of 500 psig as the peak operating pressure.

Based on that pressure then, a very straightforward program was set up to determine the end result being one hour per pound. So what we evaluated then, we started in with a series of geometries which all had the same total volume. But this evolved to be the program, the computer program, with the length, width and thickness of the cell being varied within certain limits.

(Slide 213.)



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20 AH NICKEL-HYDROGEN CELL
ORIGINAL DESIGN

FIGURE 212

1h92

This slide that's being shown, or the drawing that's being shown, shows the prismatic design evolved based on that work. I don't know if the dimensions -- can't make them out very clearly, but it's a 10 inch high cell, it's 5.8 inches wide and 1.2 inches thick.

There are certain manufacturing difficulties that we would have with this cell, and also there's other producability factors involved. The work has continued.

(Slide 214.)

What this represents is a cylindrical half cell design. And actually it is a limit condition of the previous cell. What we have are two half cells which form the cell case, which can be easily formed. We use a conventional cell stack with an internal cellcase retainer arrangement.

The advantages of this design lie mainly in the capability to manufacture something that is based on existing technology. The seals are shown, the insulators are shown in this view as being on the flat side, which would be a very low profile seal and would mate up with proper insulators from cell to cell. But since this drawing was made, it's been determined to move the seals to the radius, to the outer radius of the cell.

We will come back to that, because we show a battery design later on in the presentation, utilizing this concept. In addition to the Comsat program which, as I said, will result in both cylindrical cells and cells with prismatic cross sections, we have three other programs with prime contractors and we are negotiating a fourth.

I would like to present the highlights of one of the programs, which is with Marty Gandel and Lockheed Missiles and Space Company. This program is a development program relating to 20 ampere hour nickel-hydrogen cells. It is directed for flight qualification of nickel-hydrogen hardware.

The program utilizes existing technology as its foundation, and all components that are being used in the program are proven by virtue of other manufacturer's batteries or other flight type hardware.

The parametric cell test program is being performed as well as a series of dynamic tests. The next slide will show a photograph of the cell.

(Slide 215.)

Now, this cell differs from the previous cell that was shown, or the first slide that was shown, primarily in the area of the cover design.

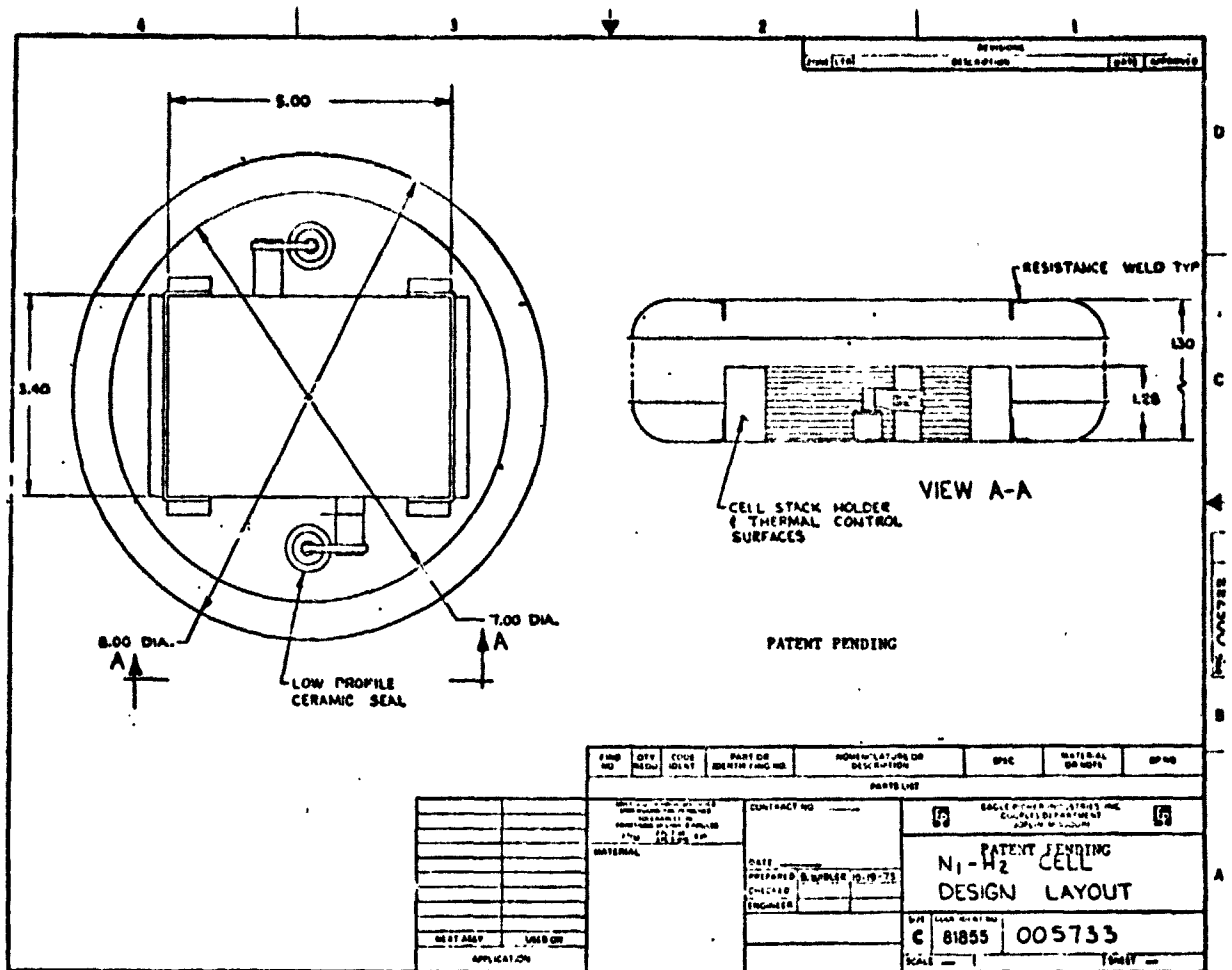


FIGURE 214

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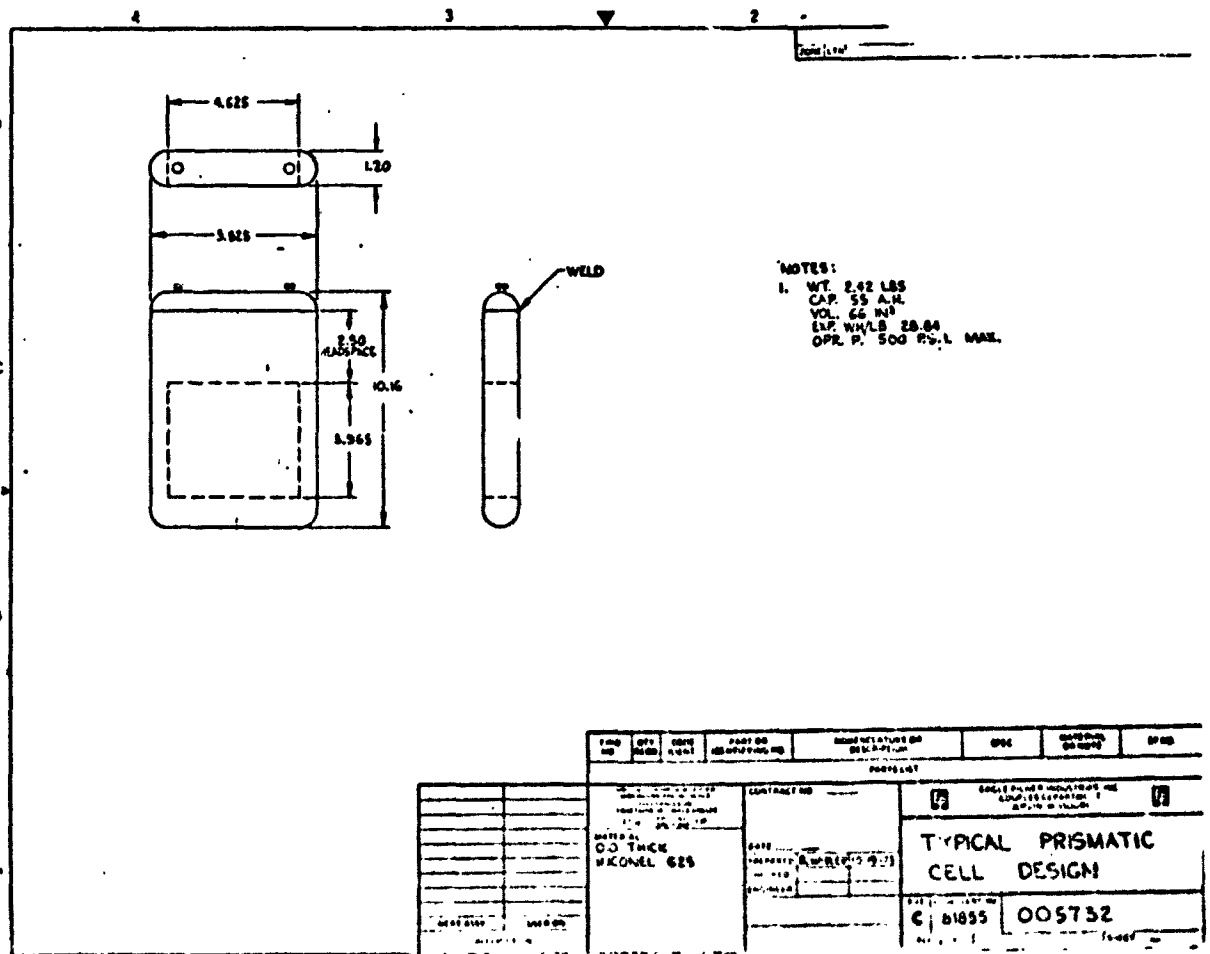


FIGURE 213

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FIGURE 215

FIGURE 216 NOT AVAILABLE

FIGURE 217 NOT AVAILABLE

FIGURE 218 NOT AVAILABLE

FIGURE 219 NOT AVAILABLE

lh93

The next slide will show a view of a drawing of what the cell is supposed to look like inside.

As you can see, it uses conventional cell stack arrangement. This design uses zirconium, nickel gold, ceramic-metal seals. It has provision for holding the plate stack in place as well as provisions for -- we'll say the general term -- of electrolyte management.

The next slide shows what the cell actually looks like.

This is an X-ray of one of our units. It shows also the ceramic seal to some degree.

The next slide is a drawing of the ceramic-metal seal.

This seal is manufactured by ILC Technology and is very similar to the seal design that was presented yesterday by Bill Harsch. It employs ninety-nine five alumina, has zirconium base braze with nickel gold brazing of the metal members to the cover.

The next slide shows the test set-up.

It shows a couple of the cells over on the right-hand side. At the time of photograph the cells are at about, something less than 500 psi.

May I have the next slide?

(Slide 220.)

This next slide is a photograph of a pressure cycle tester. What we have set up is an accelerated test for evaluating the capability of the pressure vessels. This gadget is actuated by pressure. We can set the limits of the equipment to cycle between any two points, and we can rapidly put pressure cycles on the nickel-hydrogen cell container.

It also has a timer override; in case the thing was to develop a leak overnight it would automatically sequence.

The next piece of test equipment shows, looks like an electroprop, but it is a spin tester and it relates to a question that was asked earlier regarding a spinning environment.

1h94

(Slide 221.)

The requirement we have is to spin the cell at 92 rpm for 100 hours during which time the cell is being discharged. This test was completed yesterday and with really quite gratifying results. This in a way relates to electrolyte management. It does not, of course, relate to the total problem or the total area of electrolyte management.

But it verifies that this design will maintain the electrolyte that it requires for the duration of the spin test. This particular cell, one was a dummy, and the other cell was the active cell. The initial capacity was between 19 and 20 ampere hours.

During the spin test for 100 hours the cell was being discharged at 100 milliamps through the slip rings that are shown in the slide. After 100 hours of spin, the discharge was completed at C/2 rate. The resulting capacity was greater than 16 ampere hours. Okay.

Included in our work has been a number of areas of what we consider advanced design concepts for metal oxide hydrogen batteries.

I would like the lantern slide next.

In our metal air work we designed a battery and built a battery. This slide shows the inside view of it. This is a zinc air primary battery which effects a common manifold.

The next slide shows the actual battery that was constructed so that the battery design is cylindrical.

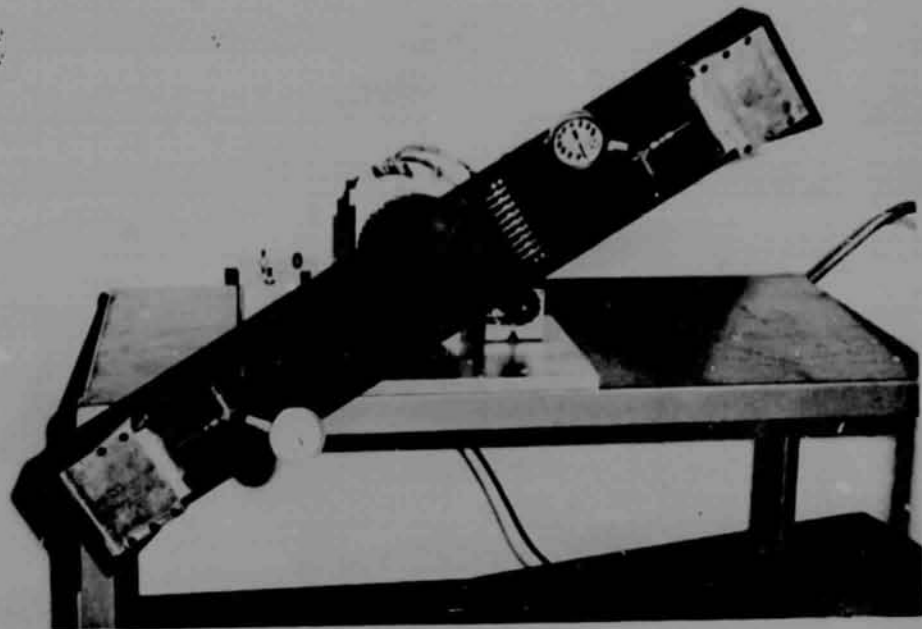
This lends itself very well to hydrogen battery technology or hydrogen battery application.

This is another concept of the common gas reservoir simply being a series of cells which are contained within a pressure vessel.

(Slide 224.)

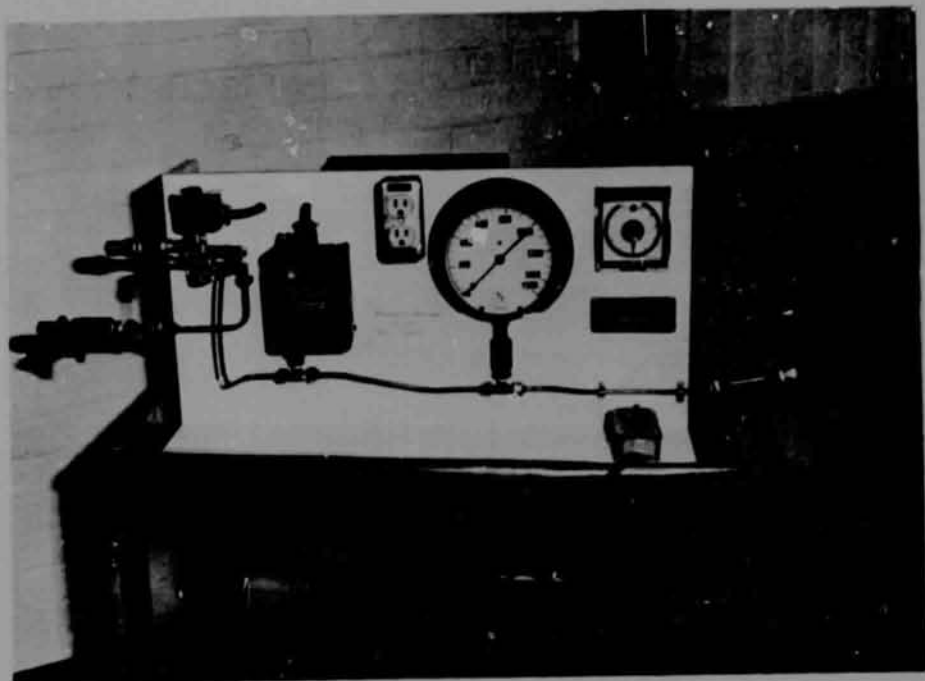
There are some precise advantages in this kind of packaging. First of all, we feel that the watt hours per pound will be increased significantly. The batteries should be less expensive, because it won't be necessary to have each cell in an individual pressure vessel. In fact, standard, ordinary, every-day rectangular cells could be packaged inside the volume.

FIGURE 222 NOT AVAILABLE



SPIN TEST EQUIPMENT
WITH MOUNTED 20 AH
NICKEL-HYDROGEN CELLS

FIGURE 221



PRESSURE TEST EQUIPMENT

FIGURE 220

1h95

And the volume, the only restraint there is what pressure do you want to operate. One real nice thing about this is there would be no negative variations in capacity from cell to cell, as all cells would run out of hydrogen gas at the same time.

Let's put up a slide.

(Slide 225.)

This is a schematic which is similar to some of the slides that you have seen earlier. It's a slide of a cylindrical shaped cell with disk shaped plates, and this type configuration will be manufactured and dynamic tested for Comsat as part of our 50 ampere hour program.

Okay, try another one.

(Slide 226.)

This is another concept for a cylindrical cell, and it is very applicable to small cells, but it would be also applicable to large cells. The exact limitation would probably be how large can we make our electrode, if we are going to spiral wind the cell for a cylindrical cell -- or spiral wind the plate for a cylindrical cell.

Okay.

(Slide 227.)

This is a schematic of a 15 ampere hour cell which is very similar to the one that we talked about earlier. I think the next shows a battery design utilizing this concept.

This shows a rack of cells of this particular geometry with restraining plates and showing some type of thermal fin arrangement for moving heat or dissipating heat to a thermal control surface.

Okay, next.

This is the larger 50 ampere hour prismatic design as optimized. May I have the book back? I'll give some weights. The book that's in the protector over there. This cell weight is predicted at 2.57 pounds, which would give us 27.2 watt hours per pound.

Can I have the half shell?

BATTERY CONFIGURATION - PIE SHAPED CELLS
COMMON GAS STORAGE

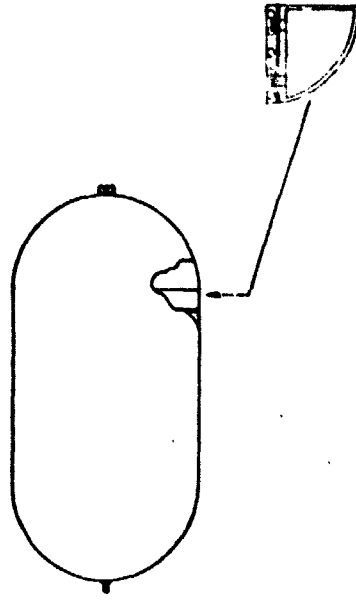


FIGURE 224

SINGLE CELL - CIRCULAR PLATE STACK

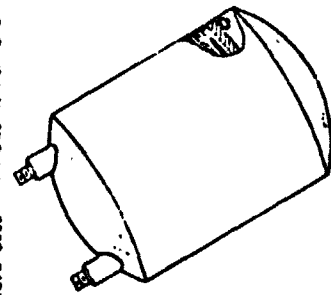


FIGURE 225

SINGLE CELL - SPIRAL WOUND

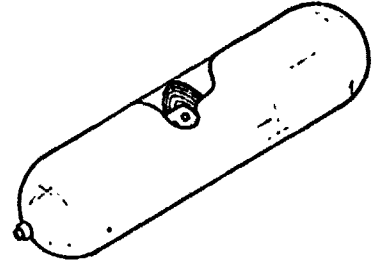


FIGURE 226

FIGURE 223 NOT AVAILABLE

15 AMPERE HOUR NI-H₂ CELL

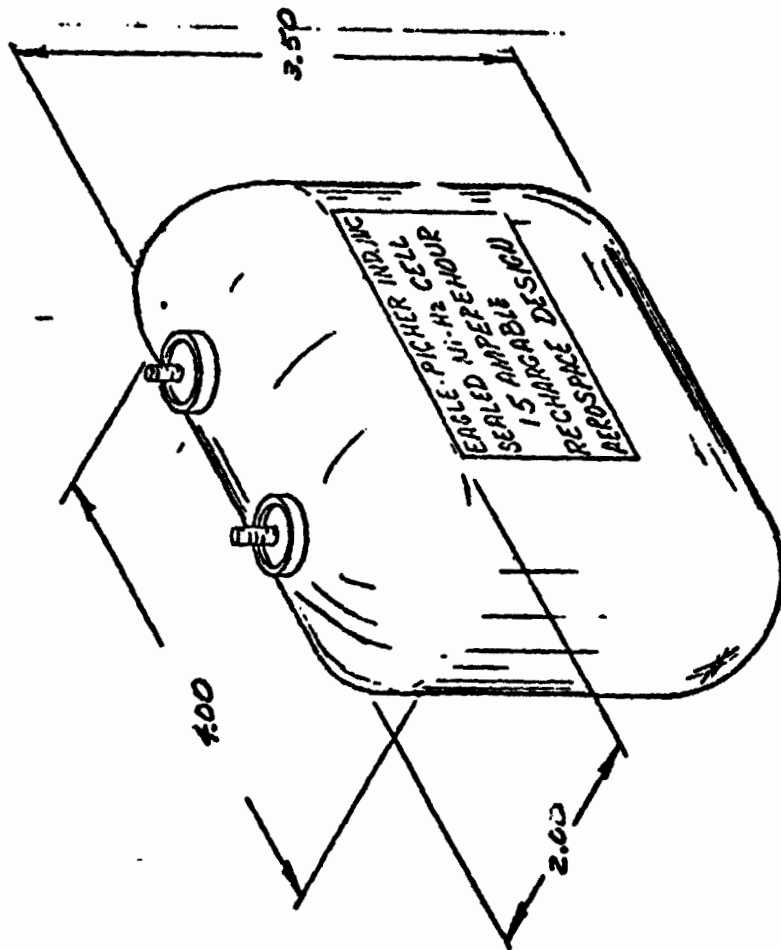


FIGURE 227

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FIGURE 228 NOT AVAILABLE

FIGURE 229 NOT AVAILABLE

FIGURE 230 NOT AVAILABLE

FIGURE 231 NOT AVAILABLE

1h96

This is the battery design for the half shell design 50 ampere hour battery as was presented earlier in the discussion of the Comsat program. In this configuration each cell is mounted adjacent to the next and then around each cell again is a heat dissipating fin which also acts as a structural reenforcement of the cell, keeping in mind that each cell will have a precharge of hydrogen on it when it is an individual cell, so that the fin or the structure support will be designed to retain that particular pressure on the cell and then also as a heat dissipator for the battery.

I think that's it. Okay, all right. This is the cell design again, for that particular battery design.

Thank you. I am ready for questions, if any.

HENDEE: Hendee, Telesat. How many G's are you running out of that?

CARR: That calculates out to be five to six G's, right, Marty?

HENDEE: Are you planning to do anything under a normal charge machine, you know, C discharge rates, charge-discharge cycles?

GANDEL: I will answer that. Gandel, Lockheed. We didn't crank in a charge requirement because the application we are thinking of would be one where there would just be a discharge period. I think it will be real interesting to try a charge on it and see -- there was a vapor entrainment question that somebody brought up that might be significant.

HENDEE: That would be interesting. I would like to see some kind of results on it.

HAAS: You didn't mention the configuration of your nickel electrode in some of your slides. Are you evaluating back to back nickel electrodes? Another question: What electrochemical efficiency are you obtaining with your nickel electrodes, your nickel-hydrogen cells as compared to nickel-cadmium?

CARR: In answer to the first question that you asked, Ron, in both programs the parametric tests or parametric design studies both include configurations of matching positive electrodes to negatives. And we refer to them quite casually as a "1 on 1" configuration or a "2 on 1" or a "2 on 2." And these configurations are being evaluated in both of the programs a little differently.

Now, the second question was what?

1h97

HAAS: The efficiency of the nickel electrodes for nickel-hydrogen as compared to nickel-cad?

CARR: We really haven't seen any difference. We are looking at an efficiency of around 90 percent, knowing what the actual positive material is in the cell.

HAAS: That is for your back to back electrodes?

CARR: Yes.

HOLLECK: Holleck, Tyco. The planning cells are not included in the weights you gave.

CARR: The weights I gave are cell weights, and as I said, we are kind of loose here. I will give you some more. On the half shell design, the cell weight will be a thousand and 98 grams which is 2.41 pounds for the cell, which is 21 watt hours per pound on the cell.

This is one thing, of course, you have to consider in battery design, whether you are considering cylindrical cells or whether you consider a cell with a prismatic cross section, is that you have to hold them together some way.

HOLLECK: I think it is only important if one compares different numbers which have been quoted. Most of the cylindrical cells do not require that and do have lower ones.

CARR: On the other hand, they do require some kind of thermal sinking to a heat controlled surface which will require some amount of weight which hasn't been determined yet -- 10 percent.

HOLLECK: I would like to make one short comment. I would say in the electrolyte management they will play a big role. One thing that has to be considered also in the evaporation mechanism is that in practice you will not have a clean cylinder wall either by entrainment or whatever mechanism

You still have some leakage in the container. Therefore, the Delta P, the pressure between the cell stack and the outside, is not really as big as it would be if you had a clean cylinder wall.

CARR: I guess I don't understand. I understand your comment but I don't see how it relates.

HOLLECK: It has been mentioned before, the question of how much temperature difference between the outside wall and the inside can you have until water transport becomes a problem. And for this one has not only to consider the difference between KOH and pure water, but one has to consider

1h98

in a practical case the water vapor difference before a more diluted KOH which might have on the cylinder walls or wherever.

CARR: One thing we like about our design, be it any one of these, not all of these but most of the designs that you saw, is that the cell stack is against the cell wall in some large degree. That's true of this half shell design as well as the large flat prismatic shape.

Typically, as you can envision, this computer printout shows that what you want to do to make the cell design harder and water repellant is to make the cell narrower. This, of course, is beneficial from a thermal standpoint also, so this was a nice thing.

But again, your radiuses are smaller, and so therefore the wall thickness of your cell case can be reduced, when you go down thinner.

HOLLECK: This may give you some back wicking, but it also can produce some thicker thermal radiance along the cell stack.

CARR: Yes, there is still going to be large void areas in the cell case. I mean this is by definition.

VINCE: Vince, Naval Research. I thought I saw in one of the drawings a number that looked like 10 mils -- is that your case thickness?

CARR: Disregard that.

BOGNER: Bogner, JPL. What is a self discharge mechanism, or is that much of a problem?

CARR: Loss of oxygen from the positive.

HOLLECK: It seems pretty rapid.

DUNLOP: Again, remember that fortunately that viewgraph that was put up was a sketch that Joe made. The point there is if you put it up, if you made this sketch right, there is a decaying rate going on there. It's higher than nickel-cadmium, somewhat higher. That is true.

We could talk about that in some detail. There is the hydrogen reduction of the nickel electrode. It's a relatively slow process, but whether it's bad or hydrogen active it's another problem. Suffice to say it does seem to be a relatively good correlation with the pressure decrease and a decrease in capacity observed.

If you go out in a week or two, it is trailing off quite a bit.

CARR: To answer your question, that one slide of

1h99

the large prismatic cell, which was 5.8 by 10 inches, does show 10 mil Inconel would be suitable for that cell design. Therein lies one of the problems with that cell. This is assuming the worst pressures that we must have, because we can get there if you can make it.

Of course, this is another trade-off. I think in most cases we will probably work at pressures greater than 400 psi, because you just can't make the pressure vessel that's so thin to work down efficiently, to work down at low pressures like 200 psi.

One thing that is really quite exciting about this hydrogen battery technology -- this is just an editorial comment -- is that we don't feel restrained by some of the old rules, and it's really quite a challenge to be able to design a battery which can really look like anything almost you want to make it.

Everything is so precise; so many ampere hours of capacity of the cell is equivalent to so much hydrogen, and so therefore, for any particular operating pressure you know what your total volume is. And then that becomes your only constraint. From that constraint then you go to your design constraint, safety margins, and how you are going to mount it, and these kind of things. I think that this is one point that I wanted to make.

That we are not constrained as to one kind of cell design, and we're not constrained to two or three.

GINER: I wanted to make a comment about the self discharge mechanism. We thought initially there would be, as you mentioned, oxygen being lost from nickel oxide. Then we made some experiments where we found that it was higher compression, indicating this was the type of thing that is produced -- is oxidized automatically by the nickel oxide.

We know that hydrogen really doesn't help the nickel oxide enough to have it explode, but interacts enough.

CARR: That's interesting. We did some years ago, 1961 or thereabouts, a whole series of bomb studies, so to speak, where different materials were put in with different gases, trying to cause something to happen. And at the time there was nothing that happened.

Whenever hydrogen was put in with positive plates. But of course, it could have been so small that it wasn't noted.

GINER: Six hundred psi, we can hear 600 psi -- it's a different situation.

GANDEL: Gandel, Lockheed. Dr. Giner, the pressure,

1h100

I don't think has -- I mean the fact that the self discharge may occur more rapidly at higher pressure, doesn't necessarily indicate that the reaction is occurring at the positive.

GINER: I think so, because you have plenty of hydrogen, you know. If that was the oxygen that was reacting on the platinum coming out from the positive and going into gasification and reacting to the platinum surface, you would have no effect of the hydrogen pressure because there is so much around.

The kinetics of the reactor are so fast. The oxygen-hydrogen combination on the platinum, especially at the very low potential of the high charging electrode. Other people have mentioned, depending on the wetting of the separator, you get also less self discharge. The electrolyte is really wetted with less of a discharge problem. I was wondering if that is the hydrogen diffusion.

Marty, you have an enclosed one.

KLEIN: Yes, I believe it's hydrogen reacting, probably not even directly with the nickel hydroxide. This serves as a reaction site, and you know nickel is a lousy hydrogen electrode. You've got a lot of area, you've got high pressure hydrogen, and it's very dependant on the electrolyte film thickness, like any fuel cell gas process.

It depends on a number of these things. The hydrogen pressure, the accessibility to the nickel sinter, and the degree of electrolyte. You can get different results, and you can get different results from cell to cell, you get different results from different nickel electrode structures.

It is not all that well scrutinized at this stage of the game beyond saying I am pretty sure that's what is happening.

PICKETT: I would like to know if anybody has the data that shows the effect of self discharge with the amount of cobalt concentration deposit.

KLEIN: Not I.

CARR: Not I.

BOGNER: Have you done much study with an open circuit stand other than a few days?

CARR: No. This is one thing that we want to do, but we just haven't done it yet.

STEINHAUER: Has anyone, including yourself, made

lh101

calculations or looked up data concerning explosive mixtures? Can you get an oxygen-hydrogen combination that if you get an arcing in the cell it would be explosive, or are we simply looking at hydrogen pressure?

DUNLOP: At least 5 percent. We're below -- well, normal charging, even up to C rate, we're below the explosive mixture.

LANDER: Less than 4 percent?

DUNLOP: It's much less than 1 percent. pressure you're talking about.

UCHIYAMA: I just want to recall a statement made at the very beginning of this meeting yesterday. The deputy director asked the question or made the statement concerning cost and so forth. Would you care to stick your neck out right now to say whether this --

DUNLOP: Let me make a simple point, and I will make this very simple. How much does it cost you to put a battery up into orbit. I bet you if you look at it on a one hour per pound basis you're tacking about one-half or one-third the cost that you're going to have. Four times the watt hours per pound in the system your costs will be less than twice as much.

I am glad you asked that question, because theoretically if you want to put it on a particular basis, your cost -- unfortunately I didn't agree with his statement in regard to batteries, because batteries already are probably the cheapest thing on a per pound basis which we are putting into a satellite, to begin with.

And frankly, the emphasis over the last few years has been in exactly the opposite direction. The cost of the battery is certainly not in the delivery of the cells. By the time we launch a battery in an INTELSAT satellite we pay, well, four to five times the cost of the actual cells themselves.

CARR: Did you hear that, Rampel?

DUNLOP: Even considering that point alone, there is a very interesting argument. If you really have a significant gain in terms of watt hours per pound, and then you look at how much it costs you to put a pound of payload in orbit, actually you are going to come up -- there is a very sound economic argument here to say the cost is reduced by the factor of two.

UCHIYAMA: Including the cost question, I think my second question is treated by what Carr said a little while ago

1h102

about manufacturing. I thought I detected some concern, just the manufacturing. It would take more QC, for example.

CARR: Well, first of all, our approach is mainly building a cell stack like we know how to build, except in this concession that I made to Comsat about building a cylindrical cell. That was negotiated very carefully. But the concerns, of course, are to keep the batteries that we make producable. It follows then that the costs will be kept down.

But still we are talking in terms of the same order of magnitude, or slightly more, for nickel hydrogen cells, as compared to spacecraft nickel-cadmium cells. Now, there was one other battery design that was presented which shows a substantial dollar savings in application.

BILLERBECK: Billerbeck, Comsat. Just to comment on Jim Dunlop's comment, we are still talking about numbers in the order of \$10,000 a pound for commercial communication spacecraft.

DUNLOP: That's an interesting point if we really think about that. You really probably have a fantastic cost saving.

GANDEL: Gandel, Lockheed. Putting the other end of that \$10,000 a pound comment on a 20 ampere hour cell, if we are talking saving one pound over a NiCd cell of 20 ampere hours, and if that cell cost us \$500 more per unit, which might be about what it would be, then that \$500 would account for the cost, added cost, Delta cost, versus your 10K a pound to put it up. So that's a bargain.

KLEIN: I would like to say one thing. You get distracted. The platinum cost in the cells that we are building is about a dollar an ampere hour, so that really doesn't count. It's really all the aerospace considerations. It really shouldn't cost any more than nickel-cadmium cells.

CARR: I concur.

UCHIYAMA: Does this mean all the testing that usually goes along with the delivery of the cell, vendor to the user, is not quite that extensive?

CARR: I don't know if we decided that or not. This is where we are, just building flight type hardware now so that I think we are learning there about how do we get these from where they are into batteries economically at a reasonable price. Maybe that will be cheaper, but I don't know if we know that.

FORD: Could we move on?

1h103

DUNLOP: We are going to have one more paper today that we do have; we are going to do that. There is some coffee in the back. We are going to go ahead with one more talk because a lot of people have some airplanes to catch, and then we can take a break for coffee and have more discussion if you want to.

The next speaker is Ron Haas from Philco-Ford.

tp 2(2)

Listen, gentlemen, if you will take your seats we would like to go ahead with this last paper, and then we will have the coffeebreak after that.

HAAS: Since last year we have continued to work at Philco in reviewing the design and performance characteristics of nickel-hydrogen, silver-hydrogen, and, as you know this morning, we have done a fair amount of work on nickel-cadmium to reduce the weight.

This is a general area of interest for our prime contractor, and we do think that there is a good deal of promise downstream somewhat on these hydrogen cells. One of our primary concerns, of course, is we fly batteries, not cells; and so in looking at possible design concepts we came up with a semi-prismatic cell design with a typical packaging approach in terms of packaging nickel-cad.

Could we use a pointer?

(Slide 231)

I would like to point out a few of the considerations here. We have a flat surface on the side of these cells. We have a T-rib thermal shunt, which is essentially identical in function to the design work that we do with nickel-cadmium.

We have found that that has worked relatively well in terms of reducing the packaging weight. Nickel-cadmium packaging weight has been reduced to about 4 percent of the total. That's the design concept that was discussed this morning. Or silver-hydrogen or nickel-hydrogen battery design -- we are looking at a cell with somewhat lighter weight so that the packaging weight for those cells would probably go up to about 10 percent based on our design analysis at this point.

Next slide, please.

(Slide 233.)

We would like to summarize some of the performance characteristics as we have found them to be in our laboratory investigation, and so I have included here both nickel-hydrogen and silver-hydrogen. We have demonstrated at this point about 700 cycles on silver-hydrogen. It's been mentioned

1h104

this afternoon that cycle life of something like a thousand to two thousand cycles has been demonstrated for nickel-hydrogen.

With energy density values, we have built and tested silver-hydrogen cells with an energy density of about 63 to 65 watt hours per pound. Our design values for nickel-hydrogen are in the order of 35 watt hours per pound. Additionally, there are certain applications where power density is fairly important.

And very interesting, the silver-hydrogen power density capability for a very, very short discharge period in the order of about a minute or so is 1.5 kw. per pound. Equivalent values based on the performance that we were obtaining for nickel-hydrogen would be about one-half that.

May I have the next slide, please?

(Slide 234.)

The battery assembly package we showed, first slide, is made up of a semi-prismatic cell container design. This particular one which we evaluated is a nominal 20 ampere hour configuration, in terms of the dimension about four inches across, three and a quarter inches tall, and the depth is about two inches.

The next slide, please.

(Slide 235.)

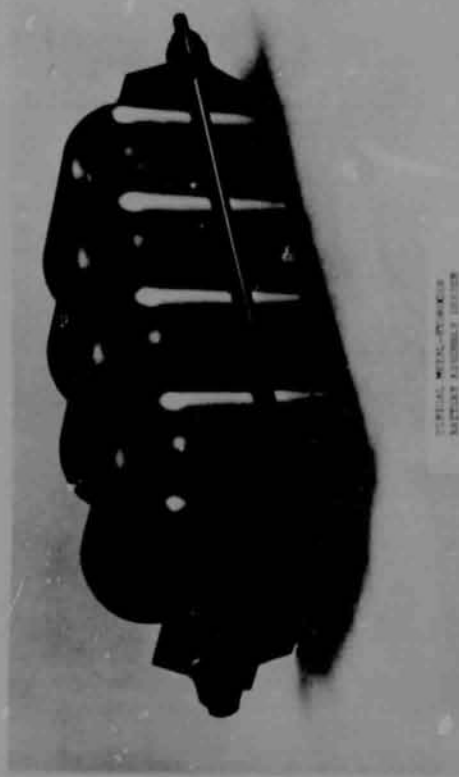
Okay. We continue to look at performance in terms of current density, a function of cell voltage, and I am going to be following this with what I think are some fairly interesting data on variations that you can expect to obtain utilizing different separator systems.

What we see here essentially is a silver-hydrogen with a somewhat lower polarization voltage, and nickel-hydrogen somewhat higher reference information here.

Next slide, please.

(Slide 236.)

Looking at separator systems -- and I do this... that we are finding out that various separator systems will give us somewhat improved performance relative to current density. We used as a baseline separator material Peilon, and we have shown a -6, -9, and -15 separator. And this data for a silver-hydrogen cell we feel is very good. And there is always a question, what have you lost in terms of cycle life capability with these separators; what are the implications in terms of electrolyte maintenance.



TYPICAL METAL-HYDROGEN
BATTERY ASSEMBLY DESIGN
PHILCO-ORCA DCB-2000 (20 AH)

FIGURE 232



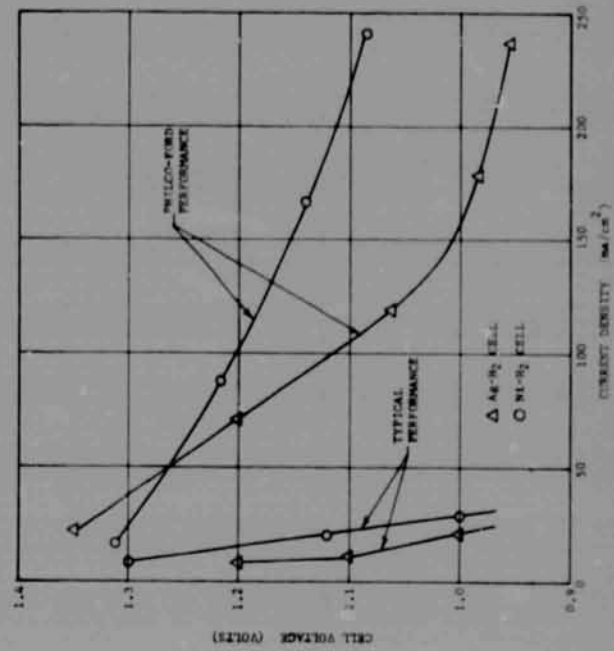
TYPICAL Ag^+H_2 CELL ASSEMBLY
PHILCO-ORCA DCB-2000, 20 AH

FIGURE 234

TYPICAL METAL-HYDROGEN BATTERY PERFORMANCE CHARACTERISTICS

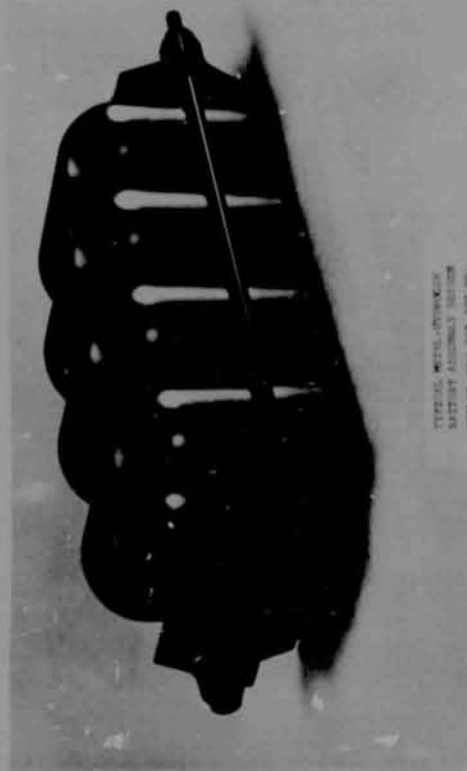
Ag^+H_2	TYPE BATTERY	Ni-H_2
$\text{Ag}_2\text{O} + \text{H}_2 \rightleftharpoons \text{Ag} + \text{H}_2\text{O}$	OVERALL REACTION	$2\text{Ni(OH)}_2 + \text{H}_2 \rightleftharpoons 2\text{Ni(OH)}_2$
700 - 1000 C	CYCLE LIFE (80% DOD)	1500 - 2000 C
30 - 95 WH/LB	ENERGY DENSITY	15 - 40 WH/LB
1.5 95/LB	POWER DENSITY	0.7 95/LB
1.2 - 1.40	CHARGE VOLTAGE	1.3 - 1.50
1.4 - 1.1V	DISCHARGE VOLTAGE	1.2 - 1.1V

FIGURE 233



COMPARISON OF METAL-HYDROGEN CELL POLARIZATION PERFORMANCE

FIGURE 235



TYPICAL METAL-HYDROGEN
BATTERY ASSEMBLY
PHILCO-1000 DCB-200-200

FIGURE 232



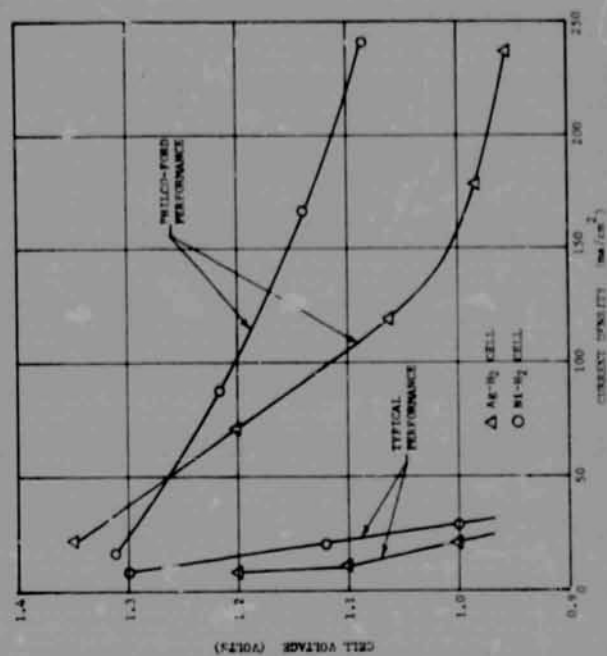
TYPICAL Ag-H_2 CELL ASSEMBLY
PHILCO-1000 DCB-200, 20 AH

FIGURE 234

TYPICAL METAL-HYDROGEN BATTERY PERFORMANCE CHARACTERISTICS

Ag-H_2	TYPE BATTERY	Ni-H_2
$\text{AgCl} + \text{H}_2 \rightleftharpoons \text{Ag} + \text{H}_2\text{O}$	OVERALL REACTION	$2\text{Ni}(\text{OH})_2 + \text{H}_2 \rightleftharpoons 2\text{Ni}(\text{OH})_2$
700 - 1000 C	CYCLE LIFE (80% DOD)	1500 - 2000 C
30 - 95 WH/LB	ENERGY DENSITY	15 - 40 WH/LB
1.5 95/LB	POWER DENSITY	0.7 95/LB
1.2 - 1.8V	CHARGE VOLTAGE	1.3 - 1.8V
1.4 - 1.1V	DISCHARGE VOLTAGE	1.3 - 1.1V

FIGURE 233



COMPARISON OF METAL-HYDROGEN CELL POLARIZATION IN PERFORMANCE

FIGURE 235

Let's go on to the next slide, please.

(Slide 237.)

The interesting thing that we have found is that utilizing Pellon in the configuration that we evaluated it, and there are probably better approaches, but for the purposes of this evaluation we compared the weight of the plates with the capacity produced.

This the values for nickel-hydrogen, silver-hydrogen on the right, and I think it's really pretty interesting to note that the efficiency, in terms of utilization of the active material, can vary quite a bit.

Next slide, please.

(Slide 238.)

Okay. The summary, in terms of the energy density and power density capability for the silver-hydrogen cells, based on calculated values, because many of these current rates would require electrode thicknesses in the order of 5 mils, and we did not evaluate electrodes with that thickness. But it's summarized here in terms of the discharge time from zero to ten minutes and then the scale changes up to 60 minutes which might be, oh, a more typical rate for the applications normally considered in satellites.

The energy density for silver-hydrogen for the longer term discharge periods is 50 to 60 watt hours per pound, and the power density for short discharge periods in the order of a couple of minutes are calculated as high as 1.5 kw. per pound.

Next slide, please.

(Slide 239.)

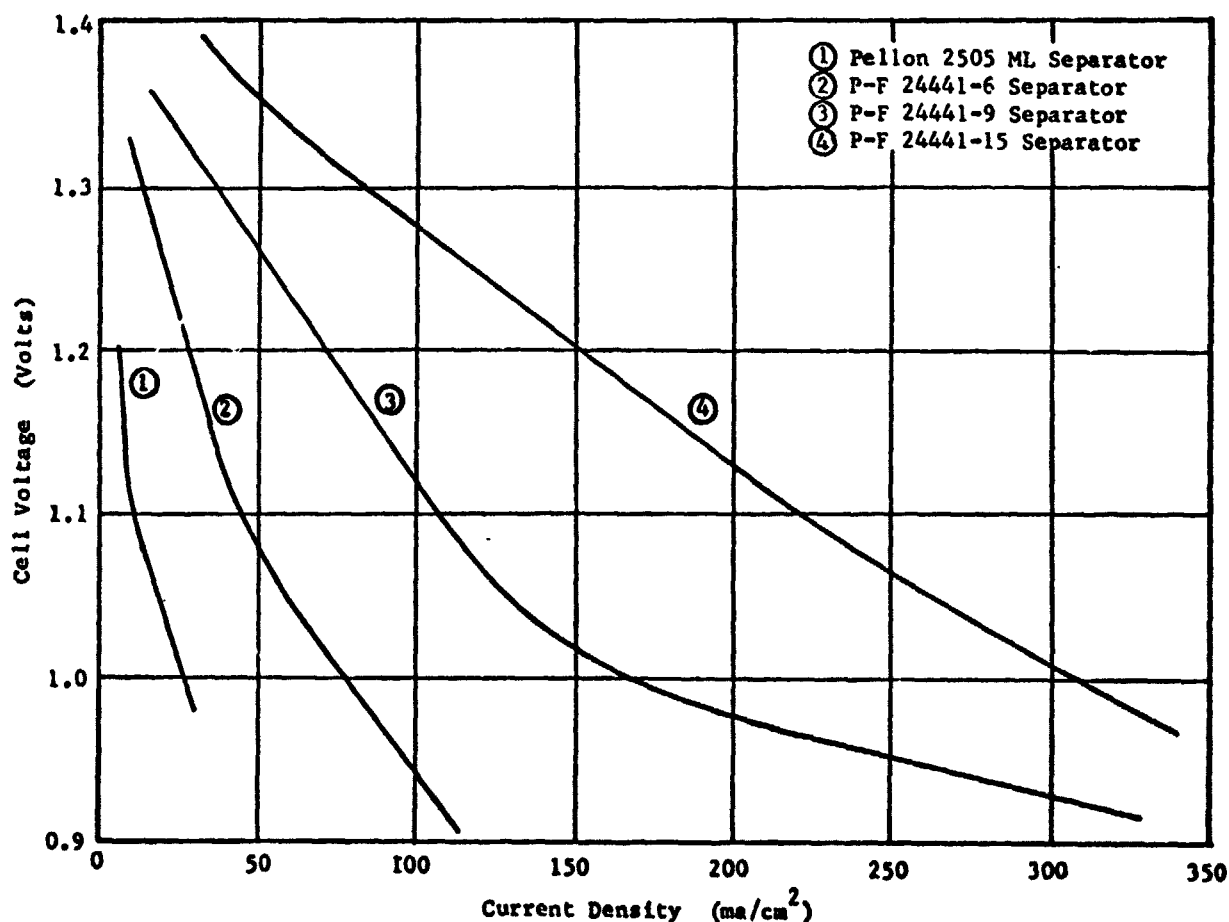
We summarize again the design values for energy density on the vertical scale, and the capacity on the horizontal scale. We have a data point for the 20 amp. hour silver-hydrogen cell. We had a laboratory cell data point for a small cell. We have design values for the 50 amp. hour silver-hydrogen cell.

The battery weight would be somewhat less than the cell weight, of course. Based on the efficiency numbers I was just referring to, grams per ampere hour on the nickel electrodes, we feel that energy density of 35 to 40 watt hours per pound should be achievable in the future. As reference, we show energy density values for nickel-cadmium batteries; and Philco-Ford, of course, is working on this problem with the nickel-cadmium, and we feel we can eventually double that value so that we would have a nickel-cadmium battery

METAL-HYDROGEN CELL ELECTRODE
EFFICIENCY FOR VARIOUS SEPARATOR MATERIALS

Ni-H ₂ CELL		Ag-H ₂ CELL
PLATE CAPACITY DENSITY	SEPARATOR MATERIAL	PLATE CAPACITY DENSITY
9.6 gms/AH	Pellon 2505 ML	3.8 gms/AH
8.1 gms/AH	P-F 24441-6	2.6 gms/AH
7.5 gms/AH	P-F 24441-9	2.3 gms/AH
6.7 gms/AH	P-F 24441-15	2.2 gms/AH

FIGURE 237



SILVER-HYDROGEN CELL POLARIZATION PERFORMANCE VERSUS SEPARATOR MATERIAL

FIGURE 236

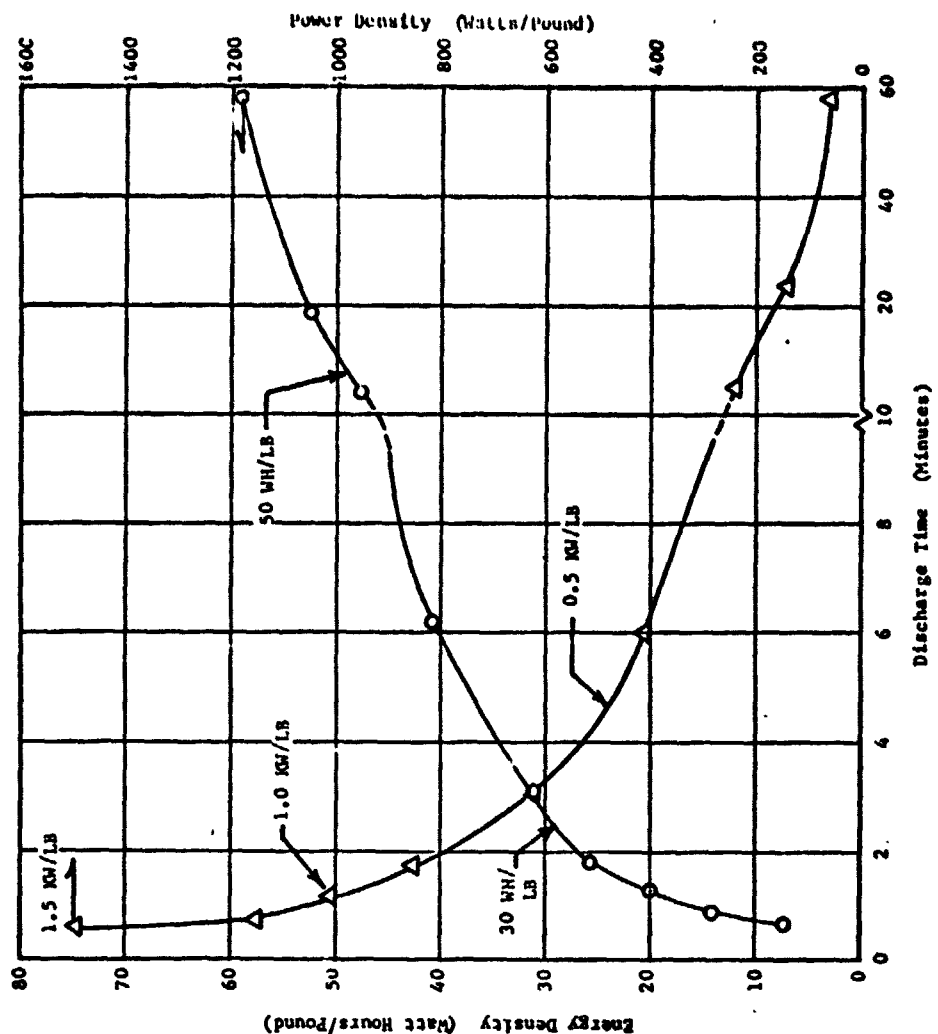


FIGURE 238
BATTERY PERFORMANCE CHARACTERISTICS
CAPACITY VERSUS ENERGY

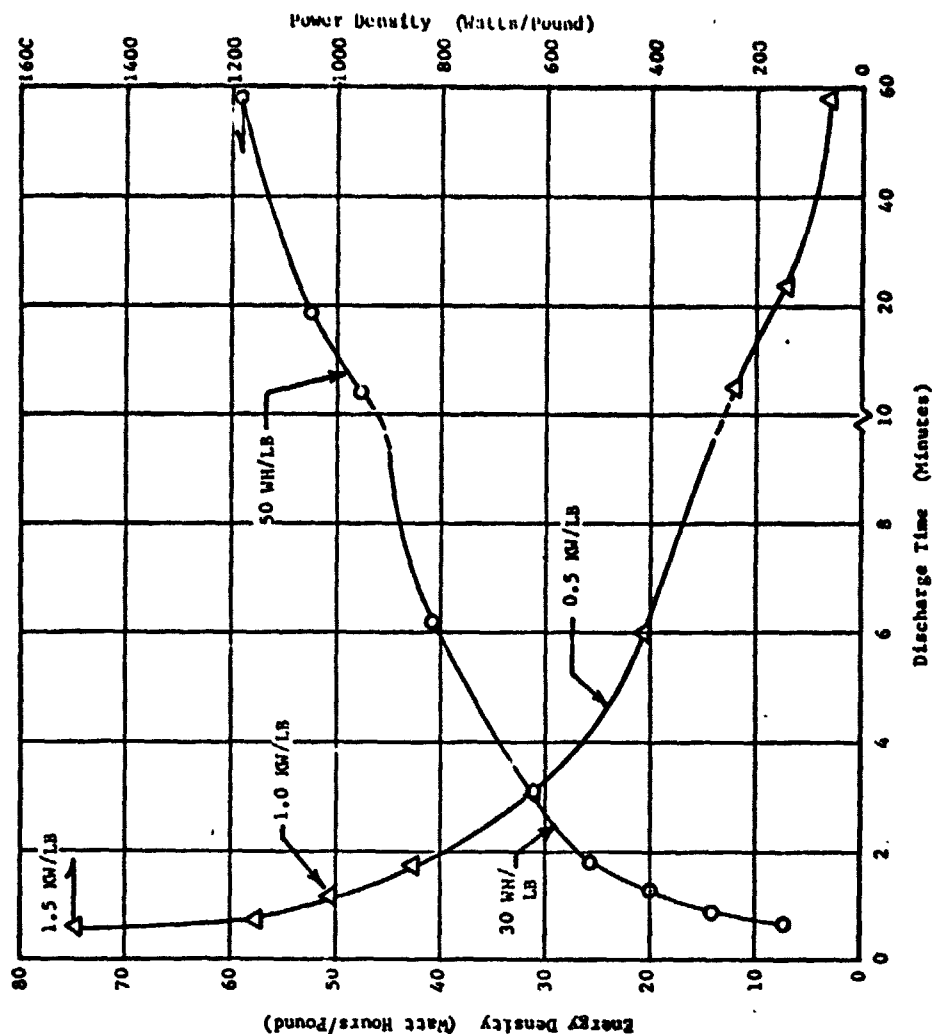


FIGURE 239
CALCULATED SILVER-HYDROGEN CELL ENERGY
AND POWER DENSITY CHARACTERISTICS

1h106 assembly energy density in the order of 24 watt hours a pound. That's the conclusion.

KLEIN: I am not sure I understand. You had a slide showing grams per ampere hour utilization of the nickel electrode as a function of separator material.

HAAS: That's correct.

KLEIN: The lowest level you had, I think, was 6.7 grams.

HAAS: Grams per ampere hour, a plate.

KLEIN: That's based on what -- the total weight?

HAAS: Based on the weight of the plate.

KLEIN: The total weight of the nickel sinter plus the active material?

HAAS: Right.

KLEIN: You have achieved that?

HAAS: Yes, that's correct.

KLEIN: What percent of theoretical utilization would that be?

HAAS: I didn't manufacture the electrode. Let me point out that it is typical of a value you would measure in a flooded nickel electrode test.

KLEIN: Why would you think that separator is dependant on a flooded cell test?

HAAS: I haven't stated this, but if you look at the data the implication has got to be there. If you are able to design a cell that is operated essentially flooded, you will achieve an efficiency similar to the efficiency you would achieve in a beaker test for a nickel electrode.

SOLTIS: I believe you showed a volume density of one and a half, one hour cubic inch for the silver-hydrogen and about half that for the nickel-hydrogen.

HAAS: I would have to refer to that. Power density or volume density?

SOLTIS: Volume density.

HAAS: I think it was power density kilowatts per pound.

1h107

SOLTIS: Do you have any numbers that you could perhaps quote for volume density?

HAAS: I think we could -- I think you could readily calculate based on the capacity and dimensions that I indicated for a 20 amp. hour cell. I would like to have that number readily available for you. I don't.

GINER: I have some reservations about this flat type battery, as you know.

HAAS: Yes.

GINER: In the first stage what happens if one of the batteries, one of the cells shorts, the pressure goes to, let's say, 50 psi at the base, and all of a sudden you had something like 600 psi in a very flimsy structure? I cannot help but think it won't fly around. You would then come to the idea that a cell should be spherical.

(Laughter.)

HAAS: Let me just show the basic geometry that we showed included this kind of arrangement in between each cell. Okay? And that in this region, away from the immediate edge of the cell, is a tie down flange which would tie down to a mounting surface. And so changes here would not really affect anything else, although it certainly would be a problem if we didn't have that kind of arrangement.

GINER: You are saying that each of the cells has a restraining set of plates?

HAAS: That's correct.

GINER: That would be very heavy if they have to be self sufficient for each of them. If they are working one cell against the other one, then the plate doesn't have to be very strong. But if you have to rely on a single set of plates --

HAAS: That's a very interesting reliability problem, and I think, in that it's a hypothetical situation and I am not sure that the battery would be functional if one of its cells shorted anyway. Yes, it's certainly something that we would consider in a system analysis relative to failure modes and effects.

DUNLOP: I think, interesting enough, just to augment this a bit, I want to call a discussion with exactly these same arguments, of course, with Earl Carr. And I was prepared, I had at least six comments against the approach, all that have been mentioned and a few more, and of course there are these considerations. I think they have actually improved that design somewhat, frankly, since that time, so there is some retention there.

1h108

By the way, they put their plates together and also support them, which may or may not help offset this problem. But it certainly is one of concern. It's interesting if you only take a look at his design, for example, that he showed, the last one he showed in his talk, which came down to that cylindrical approach for the outside can.

Then by the time he starts stacking a number of cells up together, he actually gets a cylinder, in essence, in the long run. Now, that cylinder is separated by a bunch of thin walls, each having its own separate hydrogen compartment. You can continue on along this line with a lot of different options, if you think about it with time.

And actually he pointed out a few where he had a can, a whole self contained can at one time. One of the things that will obviously happen within the next year is some evaluation of the integrity of these different pressure vessels. But frankly, it is one of the real problems in designing a battery at this point in time, in that you are really not absolutely sure of the best choice of a configuration of pressure vessel.

But at the same time, it does allow you, as Carr mentioned, a fair amount of flexibility in your thinking, because you are not inhibited at this point in time. At least you would like to think you are not inhibited by any conventional design constraint.

GINER: But the people who produce fire extinguishers in cylinders, they may stop and think of the possibilities.

DUNLOP: Then they ended up with a pressure vessel.

GINER: I think you are trying to make another nickel-cadmium because we were brought in nickel-cadmium technology. Let's start from scratch.

DUNLOP: Right, and eventually get these to the users hopefully some day, right?

BILLERBECK: You mentioned initially that one of your goals was 700 to 1,000 cycles and 80 percent depth of discharge on the silver-hydrogen?

HAAS: That's correct.

BILLERBECK: I wonder what sort of performance you actually achieved and whether there was any evidence of silver migration problems.

HAAS: Yes. We have gotten a maximum of close to 700 cycles. We have gotten less than 700 cycles on cells, too, and I think that some of the presentations on the inorganic silver-zinc separator system were very, very attractive, for

1h109

silver-hydrogen as well, because I am sure that the systems that I am evaluating now, which are in some cases not altogether different, are not optimum. Yes, there is evidence of silver migration, certainly.

KRAUSE: What kind of depth of discharge are you running some of your cells, at what temperature?

HAAS: Okay. We are probably in about the same boat as most of the people evaluating these hydrogen cells. Essentially all of it has been at a real ambient temperature. I have done some cycling as high as 95°F. I haven't really gone below like 70°F. It's a matter of program planning, and the cycling data that we have gotten in the best case has been a purely high rate charge-discharge cycling, short cycles, one hour, one and a half hour cycles.

KRAUSE: What kind of depth of discharge did you get?

HAAS: In that case it was about 80 percent, depending on whether you rated the capacity when you looked at the actual original.

KRAUSE: Does the silver-hydrogen cell go to zero pressure?

HAAS: The silver-hydrogen cell goes to zero pressure if -- oh, yes, in terms of a very high rate load, whether it's a load external to itself or internal, pressure goes to the original value.

LANDER: Do you have any discharge data for that silver?

HAAS: Yes, we have a 72 hour -- I don't know why 72 hours is a good number. The data that we obtained basically indicated that we could not measure the cell discharge rate in 72 hours for that particular configuration. So I don't have a self discharge rate, because we were not able to measure it in that case.

In other words, we had no change in pressure.

LANDER: I must say I am surprised, because we know hydrogen reacts to silver oxide.

HAAS: That's true. In this particular experiment, the cell pressure was relatively low, and so that could be a part of the reason.

STANLEY: I was wondering, in your talk about possibly making a battery, I was curious as far as the nickel-hydrogen cells for particular ampere hour size. You would compare the packing on a nickel-cadmium battery. What is the difference in the volume -- do you have any feel for that?

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HAAS: The difference in volume between nickel-hydrogen?

STANLEY: Twenty amperes compared to nickel-hydrogen.

HAAS: Yes, okay. We are currently designing for an operating pressure of about 450 psi in that 20 amp. hour cell. I don't see any reason why we couldn't go up to 700, 750. We evaluated cells with pressures up to about 900. I would suggest that the volume should be relatively close. I have done some analysis on the volume, and it is obviously a function of the pressure that you are designing for. But at about 700 to 750 psi, I think it would be equivalent in volume

DUNLOP: Yes, I agree. Let me make a comment. There are a couple trade-offs here. Everything turns out to be a trade-off when you design one of these particular cells, and one of them happens to be volume or operating pressure. It turns out that if you pick a volume, or you pick a 400 to 500 psi range, you actually have about 30 percent more of volume for nickel-hydrogen than you have for nickel-cadmium.

It turns out there is another approach that can be taken here. I really don't want to talk about it too much, but we have been running cells, storing the hydrogen in a hydride, last one a nickel hydride. We have been running these cells for a couple years now, and it turns out we did report this work at the Electrochemical Society.

If you do it with a hydride, you actually end up with less volume than you do with a nickel-cadmium cell. The other approach is to go to a high pressure. You can go to 900 or 1,000 and you end up with less volume. It's about 10 percent less than a nickel-cadmium cell if you go to that high a pressure.

It turns out the hydride works probably fairly well, but probably the reason it does is that when you charge the battery with the hydride -- and we actually use these prismatic cells that we got from Goddard, so we ran it right in a prismatic configuration, no difference basically than you have in a nickel-cad cell, with very little free volume.

It turns out that the fact that you make hydrogen before you make oxygen means that you convert most of your lanthanum nickel to lanthanum nickel hydride, and then by the time you start making any oxygen it's a very small percent of your total gas anyway still. It turns out that when you already have your hydride, you're practically completely converted to lanthanum nickel hydrogen hydride saturated, you don't seem to have much contamination problems.

So it seems to work fine. We ran it over 1200 cycles or something like that. We took it apart to look at it, but it still looks like it's working pretty well that way.

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GINER: A comment to the weight and a question. The comment: It's, I think, the volume energy density of the nickel-hydrogen battery is the same as the nickel-cadmium. If you look at your cell, I think it's about half the volume that is empty. It has about twice the energy density per cell.

DUNLOP: It actually turns out to be in that case just about 30 percent more volume.

GINER: I made a calculation It's about 600 psi

DUNLOP: Six hundred might be a tie. These are 400 psi ratings.

GINER: The question is the following: The nickel-hydrogen cell has a big advantage and that is the reversal. When you discharge the nickel electrode, you have a very optimum situation of very little heat loss. What happens to silver-hydrogen under similar conditions? Can you discharge completely the silver oxide to metallic silver all the way?

HAAS: The answer is no, of course, not completely. The efficiency, based on theoretical, and generally in the 90 percent, so no, there would be either silver metal or silver oxide, but the efficiency would not be 100 percent.

GINER: My question is, in reversal will it tolerate several hours of reversal?

HAAS: Absolutely there is no difference in the functioning of silver-hydrogen compared to nickel-hydrogen for the overcharge mode or the reversal mode.

GANDEL: Your 30 percent figure on the difference of volume, does that take into account any packaging inefficiency?

DUNLOP: No. Straight volume. With the kind of configuration that you are looking at, that's any configuration you choose. The configuration they are talking about is cylindrical. Basically there is volume there. It's basically the same number of plates. You have about 30 percent more volume at a Delta P of 400.

If you go to a higher Delta P, actually you get less.

If there are no more questions we do have some coffee in the back. Before the conference breaks up though, I would like to know if Tom Hennigan wants to make any general comment here.

HENNIGAN: I would like to thank all the speakers the last couple days for their time and effort they put into the meeting here. And you are free to use this hall or room here the rest of the afternoon for any discussions you want

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to take up. Are there any questions? Well, let's have some coffee, and if anybody wants to bring up any questions we will bring them up after about 15 minutes

Any speakers this morning or this afternoon, would they please bring up their photographs or Xeroxes of their slides and viewgraphs, yesterday too. We will take the viewgraphs if they don't have anything else.

FORD: If I could have your attention just for one minute, I would like to say this. There's a lot of people that went in to make this workshop for this two days go over, but of all the people here I don't think anybody has put as much time and effort to it as Tom Hennigan did, and let's say thank you.

(Applause)

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(Whereupon, at 4:35 p.m., the proceedings were closed.)